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VLF Nighttime Data Analysis

Telecommunication Science
Associates, Inc.

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SECTION I-1

INTRODUCTION

This report presents final results from a FY-89 VLF/LF Data Analysis task initiated in support of the VLF/LF propagation modeling program being developed by the Naval Ocean Systems Center (NOSC). Specifically, this paper gives the results of comparisons between VLF signal measurements recorded during nighttime hours and NOSC model predictions for similar nighttime propagation paths. Measured data was recorded in 1985 and 1986 aboard the merchant ship GTS Callaghan, and daytime propagation comparisons against that data were documented in the NOSC report entitled "Evaluation of the NAVOCEANSYSCEN Long Wavelength Propagation Capability Using VLF Data Collected Aboard a Ship", 01 November 1987 (termed herein *the Callaghan Report*). The present report is offered in satisfaction of CDRL A002, under D. O. 0046, Contract N66001-88-D-0033.

For many years, NOSC has developed computer programs and models for the analysis of VLF/LF propagation, and has applied this capability to a number of applications for the Navy and for other DoD agencies. These past efforts have utilized separate programs for various parts of the calculations and have generally been performed by experienced NOSC personnel capable of judging the correctness of resulting outputs.

More recently, NOSC has developed a new approach to longwave computations, whereby many parameter selections are automated, permitting reliable use by less skilled operators. This integrated program approach, called the LongWave Propagation Capability (LWPC), is now in the initial release process and is expected to find broad application within the defense community.

Verification of the program's integrity through a continuing process of comparison with existing and future VLF/LF field measurements is needed. Such comparative analyses guide the development of the ionospheric model used in the LWPC, which must be fine-tuned to assure maximum accuracy when applied to increasingly complex worldwide scenarios.

In an earlier effort by NOSC, VLF/LF data recorded on-board the merchant ship GTS Callaghan was reduced and aggregated using an HP-9000 computer, and was subsequently compared with predicted data using the LWPC model. The comparison was limited to four VLF frequencies, and to daytime-only conditions. In the present task, similar analyses of nighttime data are conducted, again limited to the VLF band.

In the sections that follow, this report summarizes certain adjustments recommended for the LWPC ionospheric model as the result of the comparisons, and gives some conclusions about analysis techniques that could be used in future comparisons. The main body of the report is given in section II, where the objectives and methodology of the analysis are stated, along with discussions of the data reduction and propagation prediction computer programs utilized in the analysis. Analysis of the Callaghan nighttime data is discussed in section II-5, and sample comparisons of predicted and measured data are presented in section II-6. Statistical evaluations of the data are shown in section II-7 along with summary charts that provide a technique for optimized selection of ionospheric profiles. Final conclusions and recommendations are discussed in section II-8.

SECTION I-2

SUMMARY AND CONCLUSIONS

This paper documents a VLF/LF Data Analysis task by the Naval Ocean Systems Center to improve the modeling of the nighttime ionosphere when making propagation predictions with the LWPC computer program. The task utilizes an extensive database of VLF measured data recorded during the 1985-1986 trips of the merchant ship GTS Callaghan in the North Atlantic area. By constraining the Callaghan data to those periods when both the ship and the distant transmitters were in time zones consistent with all-nighttime propagation, and by eliminating data from trips outside the principal area of interest, an aggregated set of recorded data was assembled for each frequency of concern. Four frequencies were examined: 16.0, 19.0, 21.4 and 24.0 kHz.

Recorded data sets were graphed as signal vs. distance plots, computing distance from the transmitter for each ship's location. The LWPC program was then utilized to compute signal vs. distance along a typical path in the same ocean area, and the predicted and recorded data were compared. By changing the LWPC parameters β and h′, which are exponential relationships describing ionospheric electron density and collision frequency profiles that vary with height, different propagation predictions were compared with the recorded data until a best fit was obtained.

In all, some 265 separate LWPC runs were compared with measured data at four frequencies, using manual overlays on a light table to find the best match between predicted and measured curves. Although this technique enabled the selection of improved $\beta-h'$ values, the method was labor intensive and required subjective judgments that became difficult at the higher frequencies. However, best-fit $\beta-h'$ values for each frequency were selected by that method, and a final confirmation was made using a statistical evaluation technique wherein average values of the means and standard deviations of the difference between recorded and predicted signal levels were graphed.

The present LWPC default values for nighttime β and h′ are 0.30-0.80 km^{-1} and 87 km, respectively. (β is entered as a range corresponding to the frequency range of 10-60 kHz; LWPC then finds β for a specific frequency by interpolation.) The analysis effort determined that a β range of 0.40-0.90, and an h′ of 85 provided a better fit between recorded and predicted data, with the improvement becoming quite significant at the lower frequencies. A preliminary recommendation for LWPC $\beta-h'$ profiles is shown in figure 1.

For the higher frequencies of 21.4 and 24.0 kHz, propagation paths from the CONUS sources of these signals fell above the 70° dip angle line for a portion of the paths (see figure 3). Since the LWPC program adjusts the default β–h′ profiles for polar cap (PCAP) effects on paths traversing areas above the 70° line, and since part of the task was to determine the validity of the PCAP default as well as that of the β–h′ profiles, the analysis of the higher frequencies became more complex. To examine PCAP effects, duplicate LWPC runs were made. Normal runs utilized the default PCAP setting of 70-74, while excursion runs set the PCAP range at 80-84, which had the effect of moving the dip angle line well above the propagation paths of interest, thus preventing automatic LWPC profile modification. The results of these tests showed better data fits for the excursion settings, indicating that the default PCAP values may require adjustment at the higher VLF frequencies. Results for both settings are shown in figure 1.

It was concluded that the present LWPC default settings for nighttime ionospheric profiles should be adjusted. Preliminary profile recommendations are to increase the β range by 0.10 km^{-1} and to decrease h′ by 2 km. The default PCAP settings of 70-74 may also require adjustment, but further data analysis is required before further suggestions may be made in this area. The following recommendations are made:

- LWPC profile optimization should be mechanized by modifying the statistical graphing program to automatically determine the average of mean and standard deviation values of recorded-minus-predicted data, for a number of distance ranges. Resulting averages should be plotted as a function of β and h′ as a means of finding truly optimized profiles for each frequency.
- The optimization of LWPC nighttime profiles should be extended over a much wider range of β–h′. This larger effort would be made feasible by the automatic statistical graphing technique suggested above.
- The more extensive LWPC runs should be facilitated by utilizing the newer, machine-independent LWPC, Version 1.0, which will permit faster runs and eliminate the need for VAX-VMS procedures.
- Daytime profile optimization of the LWPC as determined in the Callaghan Report should be re-examined, using automated statistical profile comparisons over a wider β–h′ range.
- Both daytime and nighttime comparisons should be extended to higher frequencies as measured data becomes available. At a minimum, the LF channels of the Callaghan database should be examined.

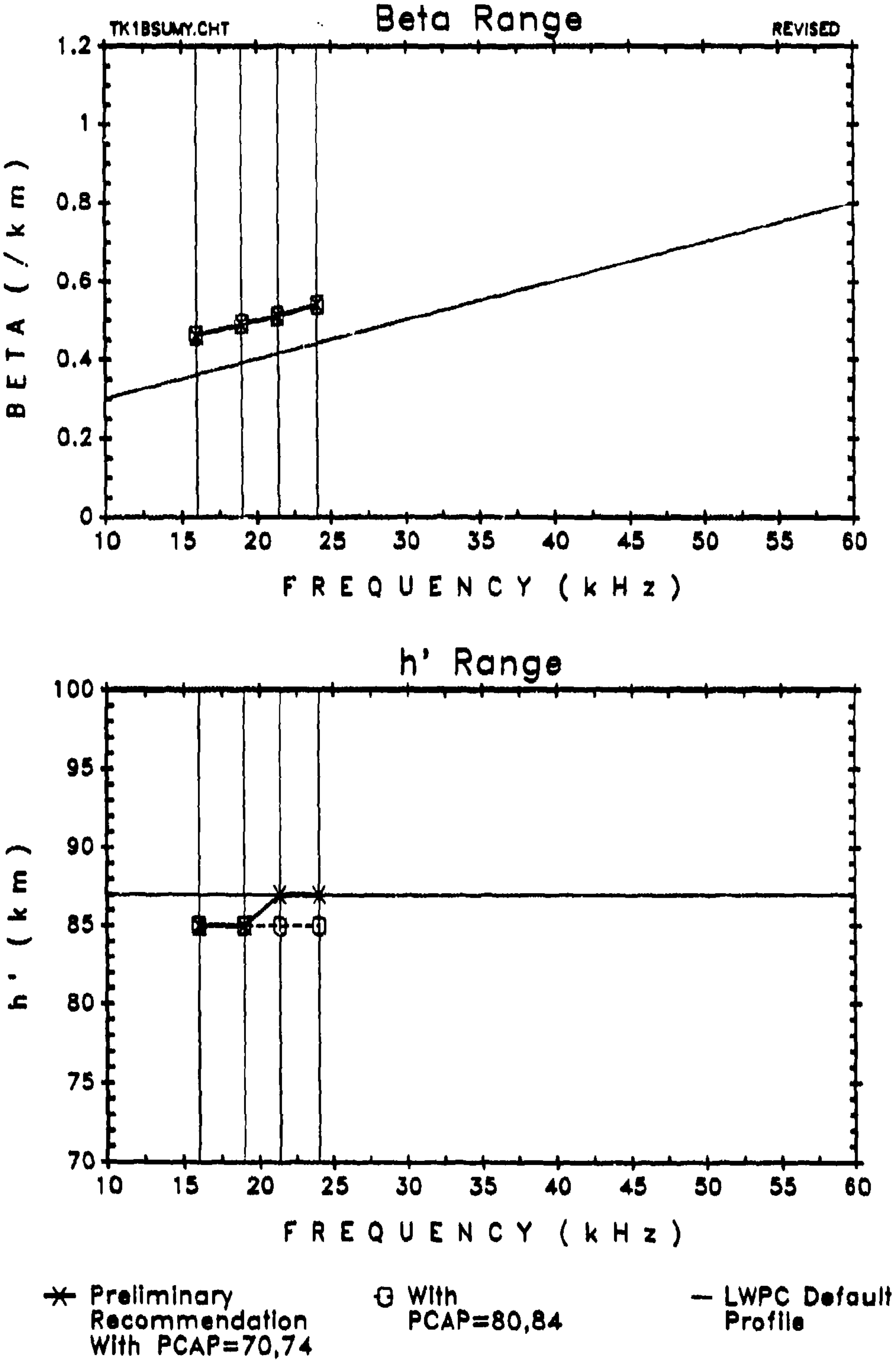


Figure 1. Preliminary recommendation, revised β–h' ranges for LWPC nighttime propagation.

SECTION II-1

OBJECTIVES

The overall task objective is to provide an in-depth comparative analysis between existing NOSC VLF/LF field-strength measurements and signal-strength predictions as generated by the LWPC computer program. A principal goal is to develop recommendations for the specification of refined LWPC ionospheric ($\beta - h'$) profiles, so that future LWPC predictions agree more closely with observed data. In this task, the analysis is constrained to VLF-band frequencies and nighttime propagation only.

An interim report* documented the following task elements:

- Review documentation and computer programs which comprise the LWPC. Perform LWPC test computations on contractor computers and compare results with similar calculations supplied by NOSC.

- Review NOSC-supplied LWPC predictions as given in the 1987 Callaghan report, and compare with daytime propagation data from the GTS Callaghan measurements. Develop a standard methodology for graphic comparison of Callaghan data with new LWPC calculations generated within the task. Compare with 1987 Callaghan report results in order to verify analysis methodology.

The present report documents results from the principal task elements, which are:

- Perform LWPC calculations for nighttime cases and compare with measurements furnished by NOSC.

- Provide comparative analyses of measured data and LWPC predictions. Provide recommendations for refinements in LWPC ionospheric model to better align measured and computed data.

*"Comparative Analysis - Callaghan Data", TCS Report TP-89-177, 31 May 1989.

SECTION II-2

METHODOLOGY

The methodology of the VLF/LF Data Analysis task was constrained by that of the Callaghan Report; every effort is made to utilize common methods and data reduction techniques to assure a continuity of results. The basic technique consists of comparing plotted data from the Callaghan recorded measurements with similar plots of LWPC signal predictions. The LWPC ionospheric profile parameters β and h' are then adjusted as necessary to obtain a best fit between the two curves.

Data-reduction programs supplied by NOSC were modified and used to produce curves of three primary types:

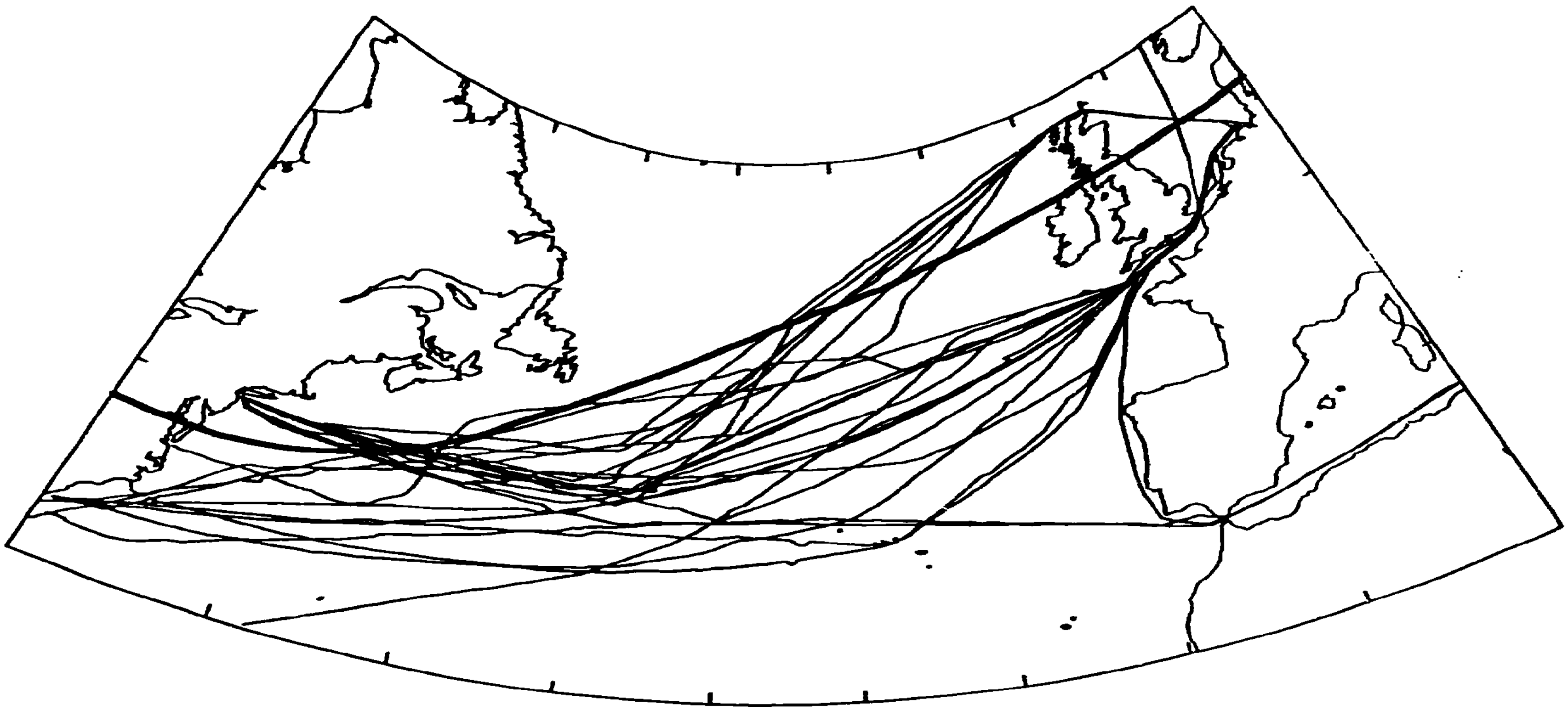
- Amplitude vs. distance plots of raw data from each trip of the GTS Callaghan.
- Amplitude vs. distance plots of aggregated data from trips grouped by number, season and/or time-of-day.
- Statistical analysis charts which permit quantitative evaluations of recorded vs. predicted data comparisons.

Data comparisons and best-fit adjustments of β and h' were made by overlaying predicted-data plots with those of aggregated recorded data, using the analyst's best judgment. Statistical analysis charts were then produced to quantify the best-fit choices.

Analysis of a typical new case (a new transmitter and/or frequency) followed these procedures:

1. Choose a transmitter, frequency, time-of-day and season. Produce plots of aggregated recorded data, selecting a group of trips by number from summary lists of ship's movements. Figure 2 illustrates a group of Callaghan trips, plotted on a gnomonic projection map.

   Individual-trip data plots may be consulted as necessary in making the selection. Alternately, data from all 50 trips may be used in the aggregated plots.



Trips: 01 02 04 05 06 07 08 09 10 11 14 15 16 17 19 20 21 24 28 37
39 43 45 47 50 52

Figure 2. Map showing Callaghan trips selected for 21.4 & 24.0 kHz, with 70° dip angle limit shown as wide line.

2. Choose a propagation path from the desired transmitter that best approximates the North Atlantic ocean area traversed by the selected ship movements. Figure 3* illustrates the four propagation paths utilized in the present task effort. The wide line denotes the position of the 70° dip angle limit.

3. Using the LWPC program, compute signal vs. distance data for the selected path, transmit frequency and radiated power level. Produce a plot for comparison with the aggregated recorded data plot.

4. Iterate the LWPC calculation as necessary over a range of ionospheric profiles. Select best-fit comparisons with the recorded data plot. It may be necessary to select several predicted data plots for later selection during the statistical analysis process.

5. Produce a statistical analysis of each best-fit selection as a plot of signal histograms vs. distance. Compute the average of the mean and standard deviation values for each applicable distance. Plot the averages as a function of β and/or h' for final best-fit selection.

Because certain of the Callaghan data trip files were found to be unsuitable, it was necessary to make a preliminary selection of recorded data to be aggregated. Section II-5 discusses the factors considered in this selection.

*The map of figure 3 was made using four stacked runs of the NOSC program WMAP. TCS has modified WMAP to permit spooling to a file, with later off-line printing on a laser printer. The map of figure 2 was generated in 1 min. 30 sec. on the AST-386 computer, and was printed in 1 min. 14 sec.

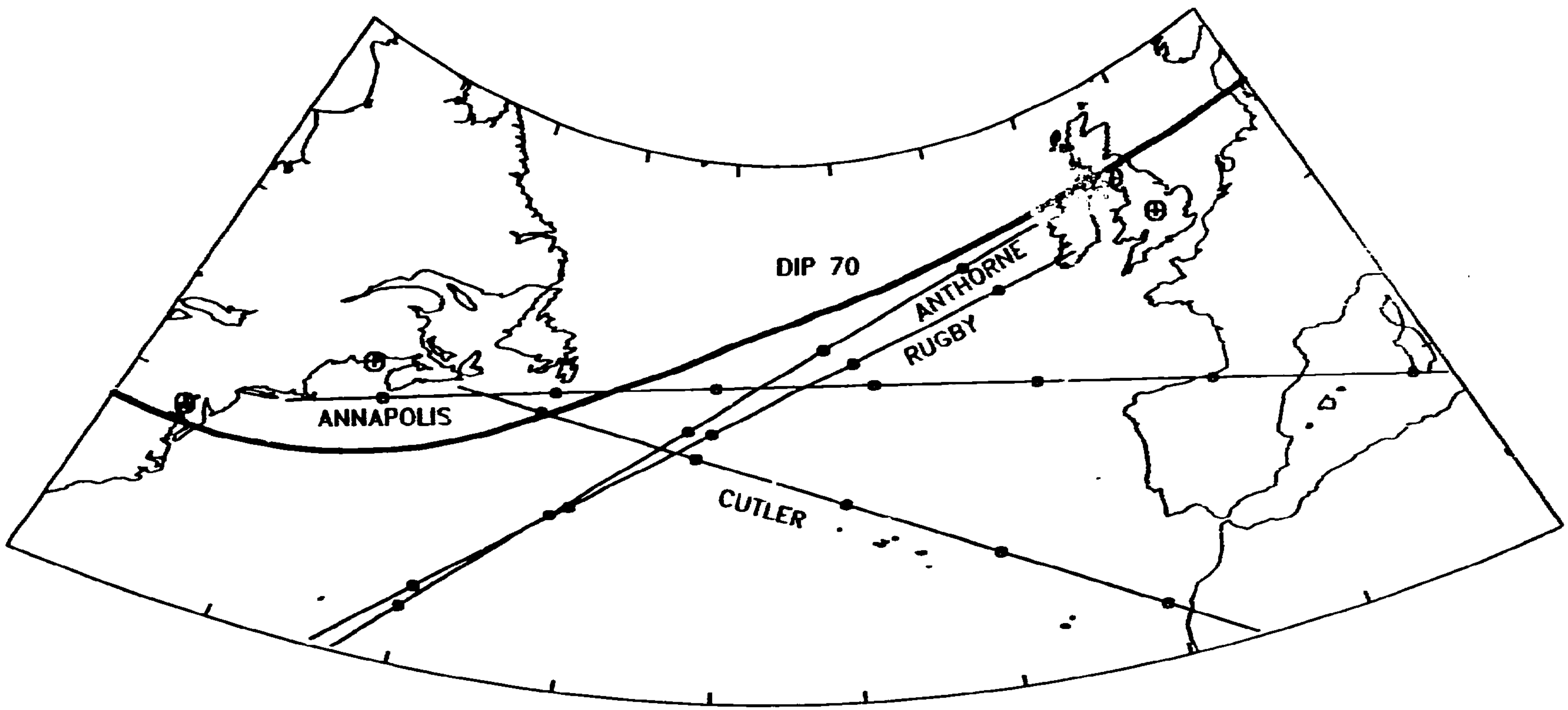


Figure 3. Propagation paths used for signal-strength calculation as a function of distance, with 70° dip angle line shown.

SECTION II-3

DATA REDUCTION COMPUTER PROGRAMS

The analysis project utilized a number of data reduction programs and supporting files that were employed by NOSC in the previous Callaghan data analysis. In all, some 80 files were received in formats suitable for use on Hewlett-Packard Model 9000 computers. The project examined all files and converted a number of the Fortran programs for execution on MS-DOS computers.

The following NOSC codes were converted and tested for routine use by the project:

- FORMIT — Forms a binary data file for a specific trip and frequency. Generates an optional plot of signal vs. distance.
- PRHEAD — Reads first and last records of FORMIT-produced binary files.
- PLOT_DIS — Produces aggregated signal data at a single frequency of selected trips for daytime, nighttime or day-night transition periods. Plots resulting signal data as a function of distance. Requires individual trip files from FORMIT as inputs.
- TRIPSTAT — Produces a statistical analysis of the difference between aggregated recorded data and predicted data vs. distance. Samples at user-selected intervals (now 125 km) are analyzed, with results plotted as histograms of the distribution from 0-dB difference, plus plots of the mean of that distribution and the level exceeded by 90% of the data. Permits user-selected constraints similar to those of PLOT_DIS, and requires FORMIT trip files and predicted signal levels as inputs.

Several data-reduction program changes and enhancements were implemented for use in the project. These changes included:

- In FORMIT, input was modified from an interactive method to that of a constant namelist filename (FORMIT.DAT).
- In FORMIT, automatic extraction of ship's start and end dates and times from the CNV files was added.

- In PLOT_DIS and TRIPSTAT, the SUBDB and DELTDB references were deleted.

- In PLOT_DIS, the redundant KFREQ parameter was deleted from namelist and the function was automatically generated from the FRQ input. Missing ordinate and abscissa labels were added.

- In FORMIT, PLOT_DIS and TRIPSTAT, laser printer and landscape switches were added.

- In FORMIT, PLOT_DIS and TRIPSTAT, optional output spooling to file was added, permitting later plotting on a laser printer in the batch mode, with print enhancements by user (linewidth, line density, size, x-y position).

- In PLOT_DIS, capability for automatic plotting of predicted data from a FASTMC.ASC file, atop recorded data plot, was added.

- In TRIPSTAT, capability for automatic input of predicted data from a FASTMC.ASC file was added.

- As initially used, PLOT_DIS and TRIPSTAT permitted ambiguous and undetected trip number errors. For example, with FORMIT data files for trips 1-20 in the working directory, a call for data from trips 1-10 or trips 11-20 yielded plots of trip 1-10 data, but were marked as called. The programs have now been corrected.

- As received, PLOT_DIS and TRIPSTAT were capable of handling data from only 20 and 19 trips, respectively. This limitation has been removed.

- PLOT_DIS and TRIPSTAT have been compiled for 32-bit operation, speeding execution of each by more than two-to-one with respect to the original 8-bit compiles.

The analysis project also converted all TRIP.NRM files of recorded data and the accompanying CNV.DAT files of ship's movement from the 52 numbered trips, and installed the files on project computers. Of the 52 numbered trips of the GTS Callaghan, data from trips 35 and 42 were found to be missing. Therefore, nighttime analysis was based on data from the remaining 50 trips.

A listing of the 50 trips of the GTS Callaghan is given in table 1, on the next page. The start and end dates and times (in Universal Time) differ slightly from those listed in table 1 of the Callaghan report, for trips 1 through 22. The dates and times of table 1 were taken directly from the CNV files of ship's movement, and were utilized in the analyses unless recorded data near the origin and/or destination were found to be inappropriate.

Table 1. GTS Callaghan Trips.

TRIP	ORIGIN	DESTINATION	START		END	
1	BAYONNE, SC	BREMMERHAVEN	03-29-85	2230	04-06-85	1700
2	BREMERHAVEN, W. GR.	CHARLESTON	04-11-85	2200	04-19-85	0900
3	CHARLESTON, SC	BAYONNE	04-20-85	0500	04-21-85	0700
4	BAYONNE	BREMERHAVEN	04-24-85	0400	05-02-85	1018
5	BREMERHAVEN	BAYONNE	05-05-85	0030	05-13-85	0830
6	BAYONNE	BREMERHAVEN	05-15-85	0242	05-22-85	0800
7	BREMERHAVEN	BAYONNE	05-23-85	2100	05-30-85	0800
8	BAYONNE	BREMERHAVEN	05-31-85	2300	06-07-85	0530
9	BREMERHAVEN	BAYONNE	06-08-85	2000	06-14-85	2000
10	BAYONNE	BREMERHAVEN	06-17-85	0400	06-23-85	0800
11	BREMERHAVEN	BAYONNE	06-25-85	0400	07-01-85	0730
12	BAYONNE	CHARLESTON	07-02-85	0100	07-03-85	0700
13	CHARLESTON	SAVANNAH	07-04-85	0500	07-04-85	0930
14	SAVANNAH	ALEXANDRIA, EGYPT	07-08-85	0430	07-19-85	0230
15	ALEXANDRIA	BREMERHAVEN	07-21-85	1400	07-27-85	2130
16	BREMERHAVEN	BAYONNE	07-29-85	0000	08-04-85	1715
17	BAYONNE	BREMERHAVEN	08-08-85	0100	08-14-85	2200
18	BREMERHAVEN	ALEXANDRIA	08-16-85	0200	08-22-85	0330
19	ALEXANDRIA	SAVANNAH	08-25-85	0700	09-06-85	0712
20	SAVANNAH, GA	BREMERHAVEN	09-10-85	0330	09-18-85	1900
21	BREMERHAVEN	NORFOLK	09-20-85	2400	09-28-85	2000
22	NORFOLK, VA	CHARLESTON	09-30-85	0119	09-30-85	1900
23	NORFOLK	CHARLESTON	10-23-85	1600	10-24-85	0800
24	CHARLESTON	ROTTERDAM, HOLLAND	10-25-85	1300	11-01-85	1700
25	ROTTERDAM	LIVERPOOL	11-03-85	1445	11-04-85	2000
26	LIVERPOOL, ENGLAND	ANTWERP	11-06-85	1534	11-07-85	1722
27	ANTWERP, BELGIUM	BREMERHAVEN	11-08-85	2400	11-09-85	0830
28	BREMERHAVEN	CHARLESTON	11-12-85	0300	11-21-85	0830
29	CHARLESTON	BAYONNE	11-22-85	0500	11-23-85	1100
30	BAYONNE	NORFOLK	11-28-85	0130	11-28-85	1000
31	NORFOLK	SAVANNAH	12-01-85	2300	12-02-85	1830
32	SAVANNAH	CRISTOBAL, PANAMA	12-05-85	1430	12-08-85	0641
33	CRISTOBAL	SAVANNAH	12-10-85	1740	12-13-85	0630
34	SAVANNAH	PUERTO CORTEZ, HONDURAS	12-17-85	0200	12-19-85	1122
35	NO DATA					
36	CRISTOBAL	JACKSONVILLE	12-23-85	2214	12-26-85	1100
37	JACKSONVILLE, FL	ZEEBRUGGE	12-29-85	0700	01-06-86	1846
38	ZEEBRUGGE, BELGIUM	BREMERHAVEN	01-08-86	0034	01-08-86	1925
39	BREMERHAVEN	BAYONNE	01-10-86	2300	01-19-86	1300
40	BAYONNE	CHARLESTON	02-04-86	2330	02-06-86	1118
41	CHARLESTON	ROTTERDAM	02-08-86	0400	02-16-86	0154
42	NO DATA					
43	BREMERHAVEN	BEAUMONT	02-22-86	0600	03-04-86	0718
44	BEAUMONT, TX	CHARLESTON	03-07-86	1830	03-08-86	0918
45	CHARLESTON	ROTTERDAM	03-09-86	0800	03-16-86	0500
46	ROTTERDAM	BOGEN, NORWAY	03-18-86	0300	03-20-86	1000
47	BOGEN	MOREHEAD CITY, NC	03-24-86	0015	04-02-86	1300
48	MOREHEAD CITY	CHARLESTON	04-05-86	0015	04-05-86	0900
49	CHARLESTON	BAYONNE	04-06-86	0500	04-07-86	0830
50	BAYONNE	ROTTERDAM	04-08-86	0100	04-15-86	0900
51	ROTTERDAM	BREMERHAVEN	04-16-86	0230	04-16-86	1101
52	BREMERHAVEN	BAYONNE	04-18-86	0100	04-25-86	1700

SECTION II-4

LWPC COMPUTER PROGRAM

LWPC, Version 0, as written for the VAX-VMS system, has been converted for use on MS-DOS computers by effort in this project and in associated programs for the Defense Nuclear Agency. LWPC was compiled for 32-bit operation on 80386 machines using the Lahey F-77L/EM-32 Fortran compiler, and executes at speeds comparable to or exceeding those of the DEC MicroVAX-II computer. Specific LWPC program modules available for project use are:

- PRESEG
- MODEFNDR
- SEGMWVGD
- MF_SW
- MERGE
- FASTMC
- PLTFMC

LWPC is executed on MS-DOS computers using the VCL (Virtual Command Language) program, which creates an environment similar to that of VAX computers using DCL (DEC Command Language). Thus, the various DCL command files created by LWPC in its automatic sequences may be used and interpreted without change. Operation follows descriptions in the NOSC LWPC User's Guide, as supplemented by a contractor-written User's Guide for MS-DOS computers.

Use of the LWPC programs was validated in two ways. First, a reference-path calculation was produced using input data from the LWPC User's Guide. A plot from this calculation was determined to be equivalent to figure D-3 of the NOSC User's Guide. Second, the LWPC was used to compute signal vs. distance data for the four curves of VLF predicted data shown in the Callaghan Report. Computations for these four paths were compared with those of the Callaghan report and documented in an earlier project report*.

*"Comparative Analysis - Callaghan Data", TCS Report TP-89-177, 31 May 1989.

A number of LWPC program changes and enhancements were implemented for use in the project. These included:

- Automatic operation under emulated VAX-VMS environment.
- Filename conventions revised to accommodate the 8 + 3 character filename limitation of MS-DOS.
- Automatic generation of Norton FILEINFO.FI files to annotate restricted filenames. Initial implementation adds path bearings and date/time tags.
- In PRESEG, four-digit power levels may now be specified.
- In PRESEG, the NPRINT function was added for automatic feed to the FASTMC command file.
- In FASTMC and PLTFMC, Amplitude/Phase vs. Distance print format (for NPRINT > 0) was changed to nine columns (instead of twelve) for easier printing on 80-column printers.
- In FASTMC, a two-column listing of distance and amplitude in an automatically-generated .ASC file was added, for use in inputting predicted data automatically to PLOT_DIS and to TRIPSTAT.
- In PLTFMC, NRPTS was added to namelist input parameters.
- In PLTFMC, landscape mode was added.
- In PLTFMC, an output switch was added to permit selection of plotter or laser printer HPGL emulation.
- In PLTFMC, output spooling to file was added, permitting later plotting on a laser printer in batch mode, with print enhancements by the user (linewidth, line density, size, x-y position, etc.).
- Automatic configuration management and archiving of all program versions by number was implemented.

SECTION II-5

MEASURED NIGHTTIME DATA

II-5.1 SELECTED TRIP SETS

Because of the relative variability of recorded nighttime signal data, with respect to the more uniform signals of the daytime environment, it was important to constrain the Callaghan measurements as much as possible before comparing with the LWPC predictions. Normalized data from each trip was examined for insured integrity at each frequency of interest, rejecting those cases where obvious anomolies in the measurements had occurred or where the ship's course was outside the area represented by the selected propagation path to be computed by the prediction model. The data reduction program PLOT_DIS was run for individual trip data at each frequency, and a reference manual of plotted data was assembled as an aid to selecting the groups of valid trips.

Individual plots of the ship's course for each trip were also made, using the Callaghan navigation files. The NOSC program WMAP was modified to permit automatic plotting of the ship's course on a world map, and a reference manual of individual trip plots was created. (Figure 2 is an example of such plots for a group of trips.)

A "Primary Trip Set" of recorded data was then selected, following the procedure diagramed in figure 4, and repeating the process for each of the four frequencies. Trip data files containing other than all-nighttime data were first eliminated. Plots of the ship's course for each trip were then examined, and trips out of the North Atlantic area of principal interest were rejected, along with several short trips in the European area and between CONUS ports. Some of the trips to Central America were retained for the 16.0- and 19.0-kHz British transmitters, since such trips appeared to provide useful data in the 6- to 8-Mm range. The Central America trips were rejected for the CONUS-based transmitters, however, since such locations were considerably removed from the propagation paths of interest. Finally, the remaining trip data was examined for integrity, rejecting files that were obviously contaminated by noise.

The remaining data files were defined as the Primary Trip Sets, and aggregated recorded data from these sets were used for the comparisons. Tables 2-5 on the following pages record the final trip selections, and indicate the reasons for rejecting individual data files using the reject codes of figure 4.

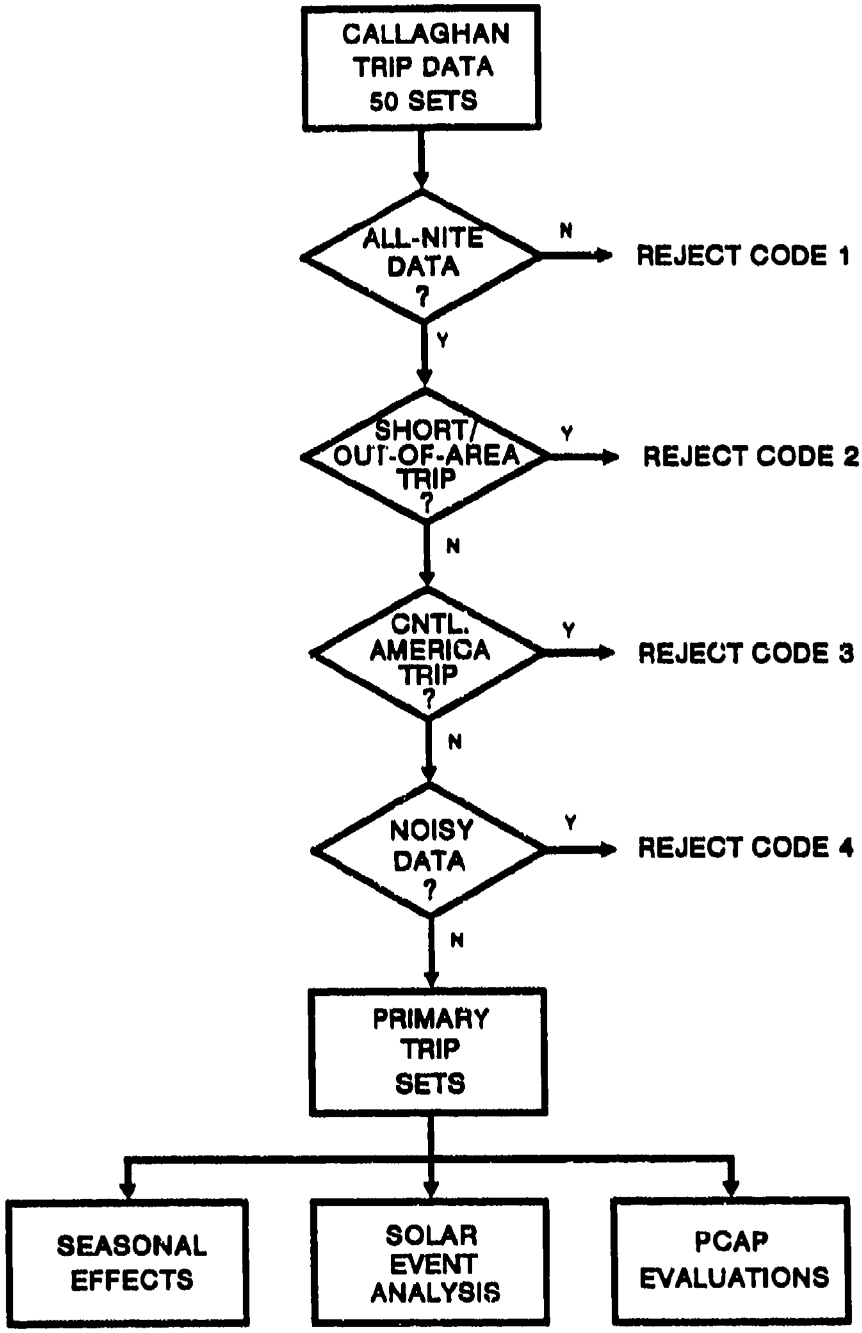


Figure 4. Methodology diagram, Callaghan trip re:orded data, selection of measured data for comparison.

Table 2. Primary trip set, 16.0 kHz (large type).

REJECT CODE	TRIP	ORIGIN	DESTINATION	START		END	
	1	BAYONNE, SC	BREMMERHAVEN	03-29-85	2230	04-06-85	1700
	2	BREMERHAVEN, W. GR.	CHARLESTON	04-11-85	2200	04-19-85	0900
2	3	CHARLESTON, SC	BAYONNE	04-20-85	0800	04-21-85	0700
	4	BAYONNE	BREMERHAVEN	04-24-85	0400	05-02-85	1018
	5	BREMERHAVEN	BAYONNE	05-05-85	0030	05-13-85	0830
4	6	BAYONNE	BREMERHAVEN	05-15-85	0242	05-22-85	0800
4	7	BREMERHAVEN	BAYONNE	05-23-85	2100	05-30-85	0800
4	8	BAYONNE	BREMERHAVEN	05-31-85	2300	06-07-85	0830
	9	BREMERHAVEN	BAYONNE	06-08-85	2000	06-14-85	2000
	10	BAYONNE	BREMERHAVEN	06-17-85	0400	06-23-85	0800
	11	BREMERHAVEN	BAYONNE	06-25-85	0400	07-01-85	0730
2	12	BAYONNE	CHARLESTON	07-02-85	0100	07-03-85	0700
1	13	CHARLESTON	SAVANNAH	07-04-85	0800	07-04-85	0830
	14	SAVANNAH	ALEXANDRIA, EGYPT	07-08-85	0430	07-19-85	0230
	15	ALEXANDRIA	BREMERHAVEN	07-21-85	1400	07-27-85	2130
	16	BREMERHAVEN	BAYONNE	07-29-85	0000	08-04-85	1715
	17	BAYONNE	BREMERHAVEN	08-08-85	0100	08-14-85	2200
2	18	BREMERHAVEN	ALEXANDRIA	08-16-85	0200	08-22-85	0330
	19	ALEXANDRIA	SAVANNAH	08-28-85	0700	09-06-85	0712
	20	SAVANNAH, GA	BREMERHAVEN	09-10-85	0330	09-18-85	1900
	21	BREMERHAVEN	NORFOLK	09-20-85	2400	09-28-85	2000
2	22	NORFOLK, VA	CHARLESTON	09-30-85	0118	09-30-85	1900
2	23	NORFOLK	CHARLESTON	10-23-85	1800	10-24-85	0800
	24	CHARLESTON	ROTTERDAM, HOLLAND	10-28-85	1300	11-01-85	1700
2	25	ROTTERDAM	LIVERPOOL	11-03-85	1446	11-04-85	2000
2	26	LIVERPOOL, ENGLAND	ANTWERP	11-06-85	1834	11-07-85	1722
2	27	ANTWERP, BELGIUM	BREMERHAVEN	11-08-85	2400	11-09-85	0830
	28	BREMERHAVEN	CHARLESTON	11-12-85	0300	11-21-85	0830
2	29	CHARLESTON	BAYONNE	11-22-85	0800	11-23-85	1100
2	30	BAYONNE	NORFOLK	11-28-85	0130	11-28-85	1000
1	31	NORFOLK	SAVANNAH	12-01-85	2300	12-02-85	1830
	32	SAVANNAH	CRISTOBAL, PANAMA	12-05-85	1430	12-08-85	0641
	33	CRISTOBAL	SAVANNAH	12-10-85	1740	12-13-85	0830
	34	SAVANNAH	PUERTO CORTEZ, HONDURAS	12-17-85	0200	12-19-85	1122
1	35	NO DATA					
	36	CRISTOBAL	JACKSONVILLE	12-23-85	2214	12-28-85	1100
	37	JACKSONVILLE, FL	ZEEBRUGGE	12-29-85	0700	01-08-86	1846
1	38	ZEEBRUGGE, BELGIUM	BREMERHAVEN	01-08-86	0854	01-08-86	1925
	39	BREMERHAVEN	BAYONNE	01-10-86	2300	01-19-86	1300
2	40	BAYONNE	CHARLESTON	02-04-86	2330	02-09-86	1118
1	41	CHARLESTON	ROTTERDAM	02-08-86	0400	02-19-86	0154
1	42	NO DATA					
	43	BREMERHAVEN	BEAUMONT	02-22-86	0600	03-04-86	0718
2	44	BEAUMONT, TX	CHARLESTON	03-07-86	1830	03-08-86	0918
	45	CHARLESTON	ROTTERDAM	03-09-86	0800	03-16-86	0500
2	46	ROTTERDAM	BOGEN, NORWAY	03-18-86	0300	03-20-86	1000
	47	BOGEN	MOREHEAD CITY, NC	03-24-86	0015	04-02-86	1300
2	48	MOREHEAD CITY	CHARLESTON	04-05-86	0015	04-05-86	0800
2	49	CHARLESTON	BAYONNE	04-0[illegible]	0800	04-07-86	0830
	50	BAYONNE	ROTTERDAM	04-09-86	0100	04-15-86	0900
1	51	ROTTERDAM	BREMERHAVEN	04-16-86	0230	04-16-86	1101
	52	BREMERHAVEN	BAYONNE	04-18-86	0100	04-25-86	1700

Table 3. Primary trip set, 19.0 kHz (large type).

REJECT CODE	TRIP	ORIGIN	DESTINATION	START		END	
	1	BAYONNE, SC	BREMMERHAVEN	03-29-85	2230	04-06-85	1700
	2	BREMERHAVEN, W. GR.	CHARLESTON	04-11-85	2200	04-19-85	0900
2	3	CHARLESTON, SC	BAYONNE	04-20-85	0800	04-21-85	0700
4	4	BAYONNE	BREMERHAVEN	04-24-85	0400	05-02-85	1018
	5	BREMERHAVEN	BAYONNE	05-05-85	0030	05-13-85	0830
	6	BAYONNE	BREMERHAVEN	05-15-85	0242	05-22-85	0800
	7	BREMERHAVEN	BAYONNE	05-23-85	2100	05-30-85	0800
	8	BAYONNE	BREMERHAVEN	05-31-85	2300	06-07-85	0530
	9	BREMERHAVEN	BAYONNE	06-08-85	2000	06-14-85	2000
	10	BAYONNE	BREMERHAVEN	06-17-85	0400	06-23-85	0800
	11	BREMERHAVEN	BAYONNE	06-25-85	0400	07-01-85	0730
2	12	BAYONNE	CHARLESTON	07-02-85	0100	07-03-85	0700
1	13	CHARLESTON	SAVANNAH	07-04-85	0800	07-04-85	0830
	14	SAVANNAH	ALEXANDRIA, EGYPT	07-08-85	0430	07-19-85	0230
	15	ALEXANDRIA	BREMERHAVEN	07-21-85	1400	07-27-85	2130
	16	BREMERHAVEN	BAYONNE	07-29-85	0000	08-04-85	1715
	17	BAYONNE	BREMERHAVEN	08-08-85	0100	08-14-85	2200
2	18	BREMERHAVEN	ALEXANDRIA	08-16-85	0800	08-22-65	0330
	19	ALEXANDRIA	SAVANNAH	08-25-85	0700	09-06-85	0712
	20	SAVANNAH, GA	BREMERHAVEN	09-10-85	0330	09-18-85	1900
	21	BREMERHAVEN	NORFOLK	09-20-85	2400	09-28-85	2000
2	22	NORFOLK, VA	CHARLESTON	09-30-85	0118	09-30-85	1900
2	23	NORFOLK	CHARLESTON	10-23-85	1900	10-24-85	0800
	24	CHARLESTON	ROTTERDAM, HOLLAND	10-25-85	1300	11-01-85	1700
2	25	ROTTERDAM	LIVERPOOL	11-03-85	1448	11-04-85	2000
2	26	LIVERPOOL, ENGLAND	ANTWERP	11-06-85	1834	11-07-85	1722
2	27	ANTWERP, BELGIUM	BREMERHAVEN	11-08-85	2400	11-09-85	0830
	28	BREMERHAVEN	CHARLESTON	11-12-85	0300	11-21-85	0830
2	29	CHARLESTON	BAYONNE	11-22-85	0800	11-23-85	1100
2	30	BAYONNE	NORFOLK	11-26-85	0130	11-28-85	1000
1	31	NORFOLK	SAVANNAH	12-01-85	2300	12-02-85	1830
	32	SAVANNAH	CRISTOBAL, PANAMA	12-05-85	1430	12-08-85	0641
	33	CRISTOBAL	SAVANNAH	12-10-85	1740	12-13-85	0630
	34	SAVANNAH	PUERTO CORTEZ, HONDURAS	12-17-85	0200	12-19-85	1122
1	35	NO DATA					
	36	CRISTOBAL	JACKSONVILLE	12-23-85	2214	12-26-85	1100
	37	JACKSONVILLE, FL	ZEEBRUGGE	12-29-85	0700	01-06-86	1846
1	38	ZEEBRUGGE, BELGIUM	BREMERHAVEN	01-08-86	0854	01-08-86	1826
	39	BREMERHAVEN	BAYONNE	01-10-86	2300	01-19-86	1300
2	40	BAYONNE	CHARLESTON	02-04-86	2330	02-06-86	1118
1	41	CHARLESTON	ROTTERDAM	02-08-86	0400	02-16-86	0154
1	42	NO DATA					
	43	BREMERHAVEN	BEAUMONT	02-22-86	0600	03-04-86	0718
2	44	BEAUMONT, TX	CHARLESTON	03-07-86	1830	03-08-86	0815
	45	CHARLESTON	ROTTERDAM	03-09-86	0800	03-16-86	0500
2	46	ROTTERDAM	BOGEN, NORWAY	03-18-86	0300	03-20-86	1000
	47	BOGEN	MOREHEAD CITY, NC	03-24-86	0015	04-02-86	1300
2	48	MOREHEAD CITY	CHARLESTON	04-05-86	0015	04-05-86	0900
2	49	CHARLESTON	BAYONNE	04-06-86	0800	04-07-86	0830
	50	BAYONNE	ROTTERDAM	04-08-86	0100	04-15-86	0900
1	51	ROTTERDAM	BREMERHAVEN	04-16-86	0230	04-16-86	1101
	52	BREMERHAVEN	BAYONNE	04-18-86	0100	04-25-86	1700

Table 4. Primary trip set, 21.4 kHz (large type).

REJECT CODE	TRIP	ORIGIN	DESTINATION	START		END	
	1	BAYONNE, SC	BREMMERHAVEN	03-29-85	2230	04-06-85	1700
	2	BREMERHAVEN, W. GR.	CHARLESTON	04-11-85	2200	04-19-85	0900
2	3	CHARLESTON, SC	BAYONNE	04-20-85	0800	04-21-85	0700
	4	BAYONNE	BREMERHAVEN	04-24-85	0400	05-02-85	1018
	5	BREMERHAVEN	BAYONNE	05-05-85	0030	05-13-85	0830
	6	BAYONNE	BREMERHAVEN	05-15-85	0242	05-22-85	0800
	7	BREMERHAVEN	BAYONNE	05-23-85	2100	05-30-85	0800
	8	BAYONNE	BREMERHAVEN	05-31-85	2300	06-07-85	0830
	9	BREMERHAVEN	BAYONNE	06-08-85	2000	06-14-85	2000
	10	BAYONNE	BREMERHAVEN	06-17-85	0400	06-23-85	0800
	11	BREMERHAVEN	BAYONNE	06-25-85	0400	07-01-85	0730
2	12	BAYONNE	CHARLESTON	07-02-85	0100	07-03-85	0700
1	13	CHARLESTON	SAVANNAH	07-04-85	0800	07-04-85	0800
	14	SAVANNAH	ALEXANDRIA, EGYPT	07-08-85	0430	07-19-85	0230
	15	ALEXANDRIA	BREMERHAVEN	07-21-85	1400	07-27-85	2130
	16	BREMERHAVEN	BAYONNE	07-29-85	0000	08-04-85	1715
	17	BAYONNE	BREMERHAVEN	08-08-85	0100	08-14-85	2200
2	18	BREMERHAVEN	ALEXANDRIA	08-16-85	0200	08-22-85	0330
	19	ALEXANDRIA	SAVANNAH	08-25-85	0700	09-06-85	0712
	20	SAVANNAH, GA	BREMERHAVEN	09-10-85	0330	09-18-85	1900
	21	BREMERHAVEN	NORFOLK	09-20-85	2400	09-28-85	2000
2	22	NORFOLK, VA	CHARLESTON	09-30-85	0115	09-30-85	1900
2	23	NORFOLK	CHARLESTON	10-23-85	1800	10-24-85	0600
	24	CHARLESTON	ROTTERDAM, HOLLAND	10-25-85	1300	11-01-85	1700
2	25	ROTTERDAM	LIVERPOOL	11-03-85	1445	11-04-85	2000
2	26	LIVERPOOL, ENGLAND	ANTWERP	11-06-85	1534	11-07-85	1722
2	27	ANTWERP, BELGIUM	BREMERHAVEN	11-08-85	2400	11-09-85	0830
	28	BREMERHAVEN	CHARLESTON	11-12-85	0300	11-21-85	0830
2	29	CHARLESTON	BAYONNE	11-22-85	0800	11-23-85	1100
2	30	BAYONNE	NORFOLK	11-26-85	0130	11-28-85	1000
1	31	NORFOLK	SAVANNAH	12-01-85	2300	12-02-85	1830
3	32	SAVANNAH	CRISTOBAL, PANAMA	12-05-85	1430	12-08-85	0641
3	33	CRISTOBAL	SAVANNAH	12-10-85	1740	12-13-85	0830
3	34	SAVANNAH	PUERTO CORTEZ, HONDURAS	12-17-85	0800	12-19-85	1122
1	35	NO DATA					
3	36	CRISTOBAL	JACKSONVILLE	12-23-85	2214	12-26-85	1100
	37	JACKSONVILLE, FL	ZEEBRUGGE	12-29-85	0700	01-06-86	1845
1	38	ZEEBRUGGE, BELGIUM	BREMERHAVEN	01-08-86	0654	01-09-86	1828
	39	BREMERHAVEN	BAYONNE	01-10-86	2300	01-19-86	1300
2	40	BAYONNE	CHARLESTON	02-04-86	2330	02-06-86	1115
1	41	CHARLESTON	ROTTERDAM	02-08-86	0400	02-18-86	0154
1	42	NO DATA					
	43	BREMERHAVEN	BEAUMONT	02-22-86	0600	03-04-86	0715
2	44	BEAUMONT, TX	CHARLESTON	03-07-86	1830	03-08-86	0915
	45	CHARLESTON	ROTTERDAM	03-09-86	0800	03-16-86	0500
2	46	ROTTERDAM	BOGEN, NORWAY	03-18-86	0300	03-20-86	1000
	47	BOGEN	MOREHEAD CITY, NC	03-24-86	0015	04-02-86	1300
2	48	MOREHEAD CITY	CHARLESTON	04-05-86	0015	04-06-86	0800
2	49	CHARLESTON	BAYONNE	04-06-86	0800	04-07-86	0830
	50	BAYONNE	ROTTERDAM	04-08-86	0100	04-15-86	0900
1	51	ROTTERDAM	BREMERHAVEN	04-16-86	0830	04-16-86	1101
	52	BREMERHAVEN	BAYONNE	04-18-86	0100	04-25-86	1700

Table 5. Primary trip set, 24.0 kHz (large type).

REJECT CODE	TRIP	ORIGIN	DESTINATION	START		END	
	1	BAYONNE, SC	BREMMERHAVEN	03-29-85	2230	04-06-85	1700
	2	BREMERHAVEN, W. GR.	CHARLESTON	04-11-85	2200	04-19-85	0900
2	3	CHARLESTON, SC	BAYONNE	04-20-85	0800	04-21-85	0700
	4	BAYONNE	BREMERHAVEN	04-24-85	0400	05-02-85	1015
	5	BREMERHAVEN	BAYONNE	05-05-85	0030	05-13-85	0830
	6	BAYONNE	BREMERHAVEN	05-15-85	0242	05-22-85	0800
	7	BREMERHAVEN	BAYONNE	05-23-85	2100	05-30-85	0800
	8	BAYONNE	BREMERHAVEN	05-31-85	2300	06-07-85	0530
	9	BREMERHAVEN	BAYONNE	06-08-85	2000	06-14-85	2000
	10	BAYONNE	BREMERHAVEN	06-17-85	0400	06-23-85	0800
	11	BREMERHAVEN	BAYONNE	06-25-85	0400	07-01-85	0730
2	12	BAYONNE	CHARLESTON	07-02-85	0100	07-03-85	0700
1	13	CHARLESTON	SAVANNAH	07-04-85	0800	07-04-85	0900
	14	SAVANNAH	ALEXANDRIA, EGYPT	07-08-85	0430	07-19-85	0230
	15	ALEXANDRIA	BREMERHAVEN	07-21-85	1400	07-27-85	2130
	16	BREMERHAVEN	BAYONNE	07-29-85	0000	08-04-85	1715
	17	BAYONNE	BREMERHAVEN	08-08-85	0100	08-14-85	2200
2	18	BREMERHAVEN	ALEXANDRIA	08-19-85	0800	08-22-85	0830
	19	ALEXANDRIA	SAVANNAH	08-25-85	0700	09-06-85	0712
	20	SAVANNAH, GA	BREMERHAVEN	09-10-85	0330	09-18-85	1900
	21	BREMERHAVEN	NORFOLK	09-20-85	2400	09-28-85	2000
2	22	NORFOLK, VA	CHARLESTON	09-30-85	0119	09-30-85	1900
2	23	NORFOLK	CHARLESTON	10-23-85	1900	10-24-85	0800
	24	CHARLESTON	ROTTERDAM, HOLLAND	10-25-85	1300	11-01-85	1700
2	25	ROTTERDAM	LIVERPOOL	11-03-85	1445	11-04-85	2000
2	26	LIVERPOOL, ENGLAND	ANTWERP	11-06-85	1534	11-07-85	1722
2	27	ANTWERP, BELGIUM	BREMERHAVEN	11-08-85	2400	11-09-85	0830
	28	BREMERHAVEN	CHARLESTON	11-12-85	0300	11-21-85	0830
2	29	CHARLESTON	BAYONNE	11-22-85	0600	11-23-85	1100
2	30	BAYONNE	NORFOLK	11-26-85	0130	11-28-85	1000
1	31	NORFOLK	SAVANNAH	12-01-85	2300	12-02-85	1500
3	32	SAVANNAH	CRISTOBAL, PANAMA	12-05-85	1430	12-08-85	0641
3	33	CRISTOBAL	SAVANNAH	12-10-85	1740	12-15-85	0830
3	34	SAVANNAH	PUERTO CORTEZ, HONDURAS	12-17-85	0200	12-19-85	1122
1	35	NO DATA					
3	36	CRISTOBAL	JACKSONVILLE	12-23-85	2214	12-26-85	1100
	37	JACKSONVILLE, FL	ZEEBRUGGE	12-29-85	0700	01-06-86	1845
1	38	ZEEBRUGGE, BELGIUM	BREMERHAVEN	01-08-86	0654	01-08-86	1925
	39	BREMERHAVEN	BAYONNE	01-10-86	2300	01-19-86	1300
2	40	BAYONNE	CHARLESTON	02-04-86	2330	02-06-86	1118
1	41	CHARLESTON	ROTTERDAM	02-08-86	0400	02-16-86	0154
1	42	NO DATA					
	43	BREMERHAVEN	BEAUMONT	02-22-86	0600	03-04-86	0715
2	44	BEAUMONT, TX	CHARLESTON	03-07-86	1800	03-08-86	0815
	45	CHARLESTON	ROTTERDAM	03-09-86	0800	03-16-86	0500
2	46	ROTTERDAM	BOGEN, NORWAY	03-18-86	0300	03-20-86	1000
	47	BOGEN	MOREHEAD CITY, NC	03-24-86	0015	04-02-86	1300
2	48	MOREHEAD CITY	CHARLESTON	04-05-86	0015	04-05-86	0900
2	49	CHARLESTON	BAYONNE	04-06-86	0800	04-07-86	0830
	50	BAYONNE	ROTTERDAM	04-08-86	0100	04-15-86	0900
1	51	ROTTERDAM	BREMERHAVEN	04-10-86	0230	04-10-86	1101
	52	BREMERHAVEN	BAYONNE	04-18-86	0100	04-25-86	1700

II-5.2 SEASONAL EFFECTS

An attempt was made to separate the recorded data into groups, sorted by season. Table 6 shows the 50 Callaghan trips divided into the three-month seasons of spring, summer, autumn and winter, with the four periods defined by the summer solstice on June 21 and the winter solstice on December 22. Similarly, six-month "warm" and "cold" seasons were defined around the same dates.

It was decided, however, that the Callaghan database was too small to support meaningful separation by season. Figures 5-8 illustrate the recorded data from the Rugby transmitter broadcasting at 16 kHz, separated into spring, summer, autumn and winter groupings, respectively, as an example case. Overlays of these plots revealed similar patterns of recorded signal with distance – there were no pronounced seasonal effects that would justify the use of different ionospheric models in the LWPC.

Similar conclusions were reached in comparing the six-month seasonal data. Again, the great variability of nighttime data due to undefined changes in the propagation channel seemed to obscure any effects that were purely seasonal.

Table 6. Callaghan trips divided by season.

	TRIP	ORIGIN	DESTINATION	START		END		
WARM SEASON	1	BAYONNE, SC	BREMMERHAVEN	03-29-85	2230	04-06-85	1700	SPRING
	2	BREMERHAVEN, W. GR.	CHARLESTON	04-11-85	2200	04-19-85	0900	
	3	CHARLESTON, SC	BAYONNE	04-20-85	0500	04-21-85	0700	
	4	BAYONNE	BREMERHAVEN	04-24-85	0400	05-02-85	1018	
	5	BREMERHAVEN	BAYONNE	05-05-85	0030	05-13-85	0830	SUMMER
	6	BAYONNE	BREMERHAVEN	05-15-85	0242	05-22-85	0800	
	7	BREMERHAVEN	BAYONNE	05-23-85	2100	05-30-85	0800	
	8	BAYONNE	BREMERHAVEN	05-31-85	2300	06-07-85	0530	
	9	BREMERHAVEN	BAYONNE	06-08-85	2000	06-14-85	2000	
	10	BAYONNE	BREMERHAVEN	06-17-85	0400	06-23-85	0800	
	11	BREMERHAVEN	BAYONNE	06-25-85	0400	07-01-85	0730	
	12	BAYONNE	CHARLESTON	07-02-85	0100	07-03-85	0700	
	13	CHARLESTON	SAVANNAH	07-04-85	0500	07-04-85	0930	
	14	SAVANNAH	ALEXANDRIA, EGYPT	07-08-85	0430	07-19-85	0230	
	15	ALEXANDRIA	BREMERHAVEN	07-21-85	1400	07-27-85	2130	
	16	BREMERHAVEN	BAYONNE	07-29-85	0000	08-04-85	1715	
	17	BAYONNE	BREMERHAVEN	08-08-85	0100	08-14-85	2200	AUTUMN
	18	BREMERHAVEN	ALEXANDRIA	08-16-85	0200	08-22-85	0330	
	19	ALEXANDRIA	SAVANNAH	08-25-85	0700	09-06-85	0712	
	20	SAVANNAH, GA	BREMERHAVEN	09-10-85	0330	09-18-85	1900	
COLD SEASON	21	BREMERHAVEN	NORFOLK	09-20-85	2400	09-28-85	2000	
	22	NORFOLK, VA	CHARLESTON	09-30-85	0119	09-30-85	1900	
	23	NORFOLK	CHARLESTON	10-23-85	1800	10-24-85	0800	
	24	CHARLESTON	ROTTERDAM, HOLLAND	10-25-85	1300	11-01-85	1700	
	25	ROTTERDAM	LIVERPOOL	11-03-85	1445	11-04-85	2000	WINTER
	26	LIVERPOOL, ENGLAND	ANTWERP	11-06-85	1534	11-07-85	1722	
	27	ANTWERP, BELGIUM	BREMERHAVEN	11-08-85	2400	11-09-85	0830	
	28	BREMERHAVEN	CHARLESTON	11-12-85	0300	11-21-85	0830	
	29	CHARLESTON	BAYONNE	11-22-85	0800	11-23-85	1100	
	30	BAYONNE	NORFOLK	11-28-85	0130	11-28-85	1000	
	31	NORFOLK	SAVANNAH	12-01-85	2300	12-02-85	1830	
	32	SAVANNAH	CRISTOBAL, PANAMA	12-05-85	1430	12-08-85	0641	
	33	CRISTOBAL	SAVANNAH	12-10-85	1740	12-13-85	0630	
	34	SAVANNAH	PUERTO CORTEZ, HONDURAS	12-17-85	0200	12-19-85	1122	
	35	NO DATA						
	36	CRISTOBAL	JACKSONVILLE	12-23-85	2214	12-26-85	1100	
	37	JACKSONVILLE, FL	ZEEBRUGGE	12-29-85	0700	01-06-86	1845	
	38	ZEEBRUGGE, BELGIUM	BREMERHAVEN	01-08-86	0654	01-08-86	1925	
	39	BREMERHAVEN	BAYONNE	01-10-86	2300	01-19-86	1300	
	40	BAYONNE	CHARLESTON	02-04-86	2330	02-06-86	1115	SPRING
	41	CHARLESTON	ROTTERDAM	02-08-86	0400	02-16-86	0154	
	42	NO DATA						
	43	BREMERHAVEN	BEAUMONT	02-22-86	0600	03-04-86	0715	
	44	BEAUMONT, TX	CHARLESTON	03-07-86	1830	03-08-86	0915	
	45	CHARLESTON	ROTTERDAM	03-09-86	0800	03-16-86	0500	
WARM	46	ROTTERDAM	BOGEN, NORWAY	03-18-86	0300	03-20-86	1000	
	47	BOGEN	MOREHEAD CITY, NC	03-24-86	0015	04-02-86	1300	
	48	MOREHEAD CITY	CHARLESTON	04-05-86	0015	04-05-86	0900	
	49	CHARLESTON	BAYONNE	04-06-86	0800	04-07-86	0830	
	50	BAYONNE	ROTTERDAM	04-08-86	0100	04-15-86	0900	
	51	ROTTERDAM	BREMERHAVEN	04-16-86	0230	04-16-86	1101	
	52	BREMERHAVEN	BAYONNE	04-18-86	0100	04-25-86	1700	

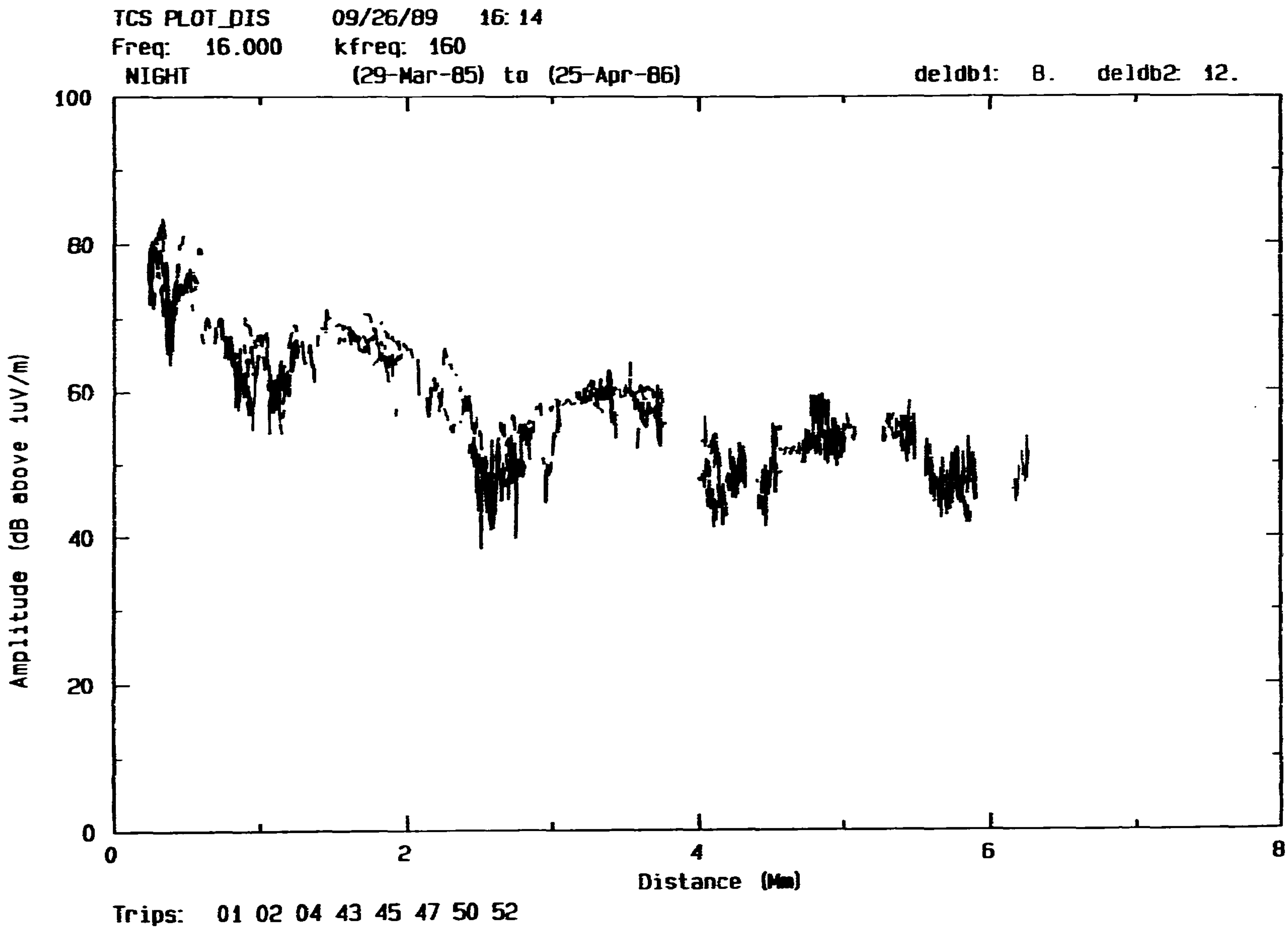


Figure 5. Typical recorded data for Spring season, Rugby at 16.0 kHz

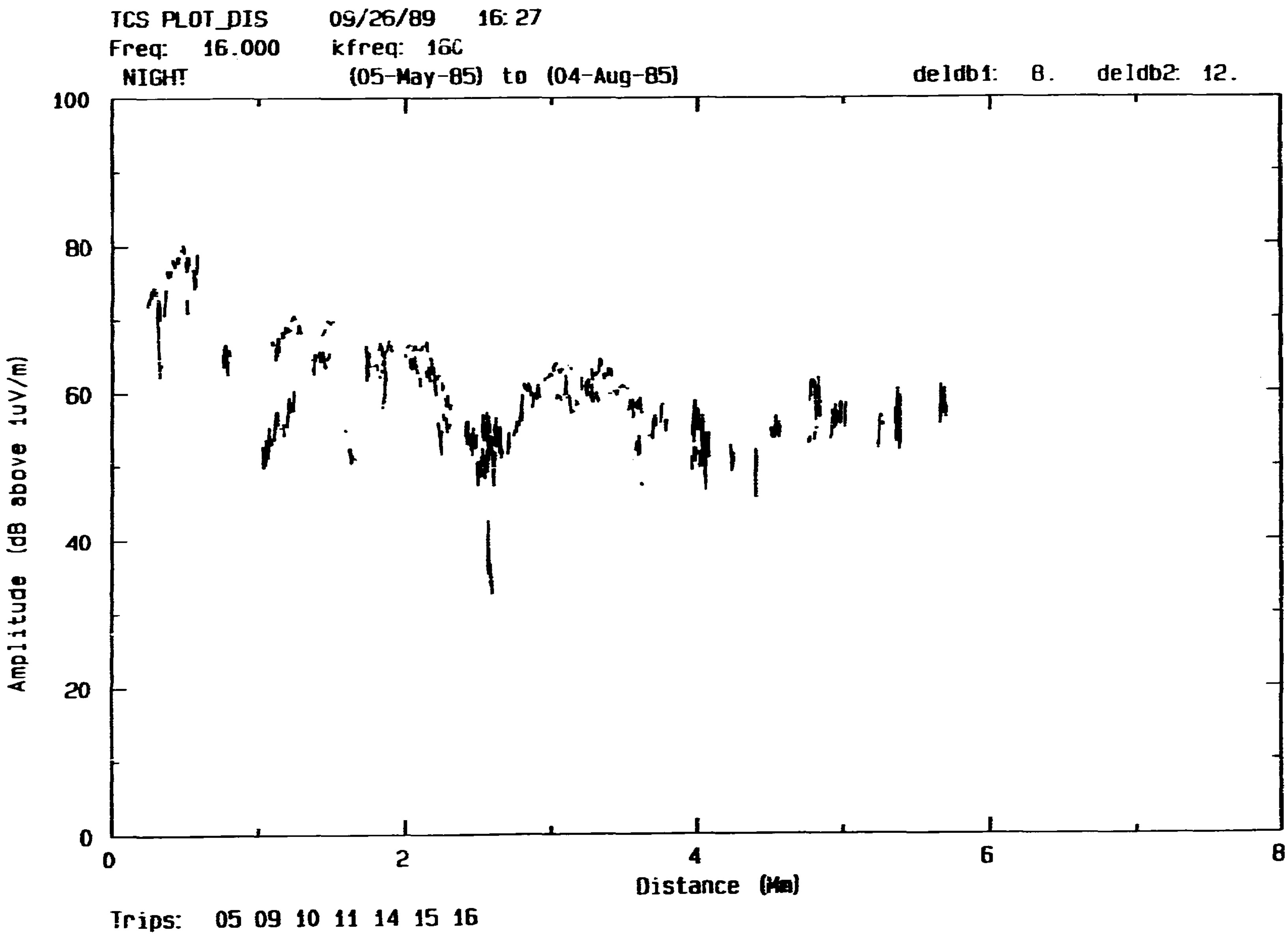


Figure 6. Typical recorded data for Summer season, Rugby at 16.0 kHz.

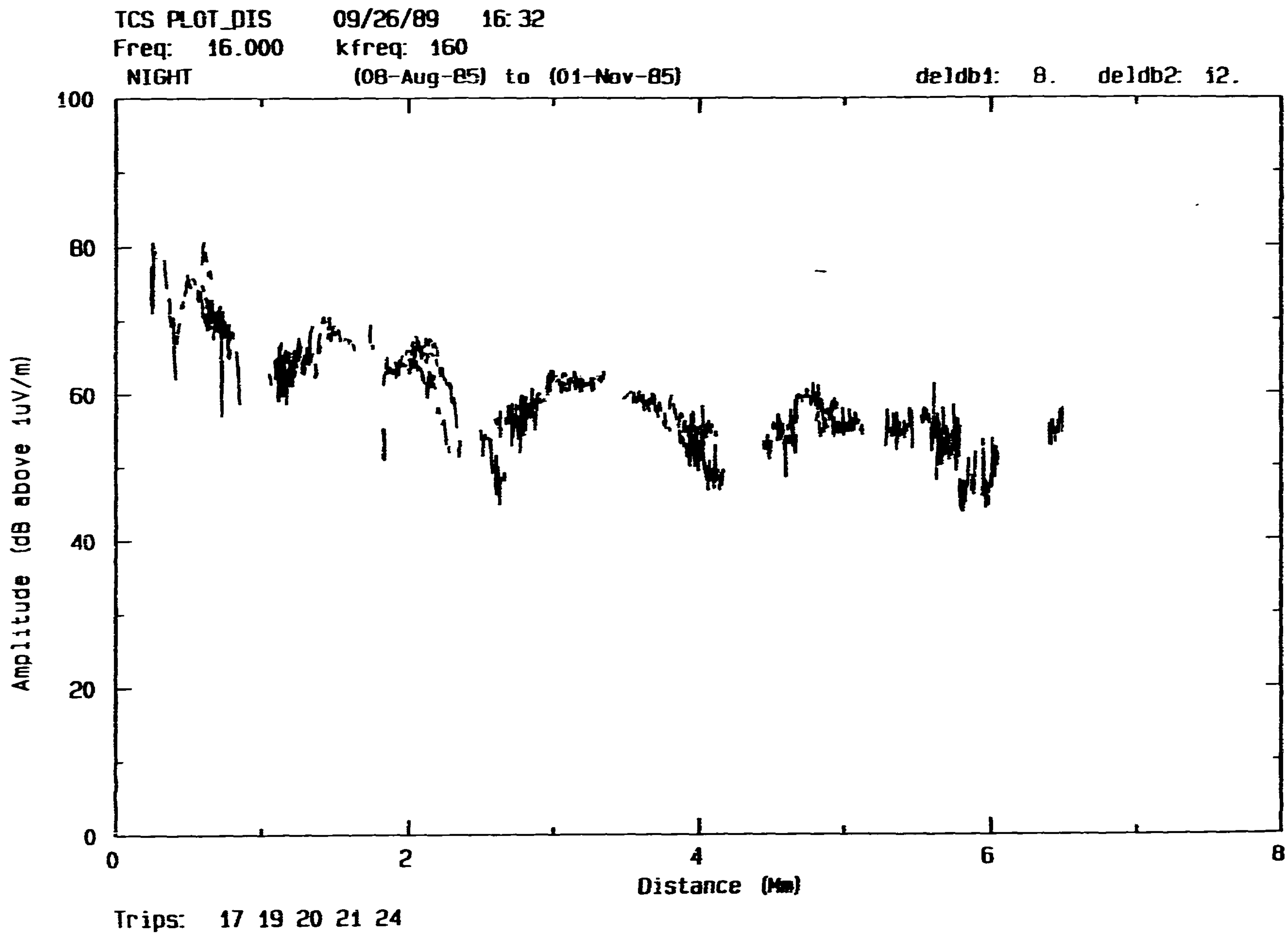


Figure 7. Typical recorded data for Autumn season, Rugby at 16.0 kHz.

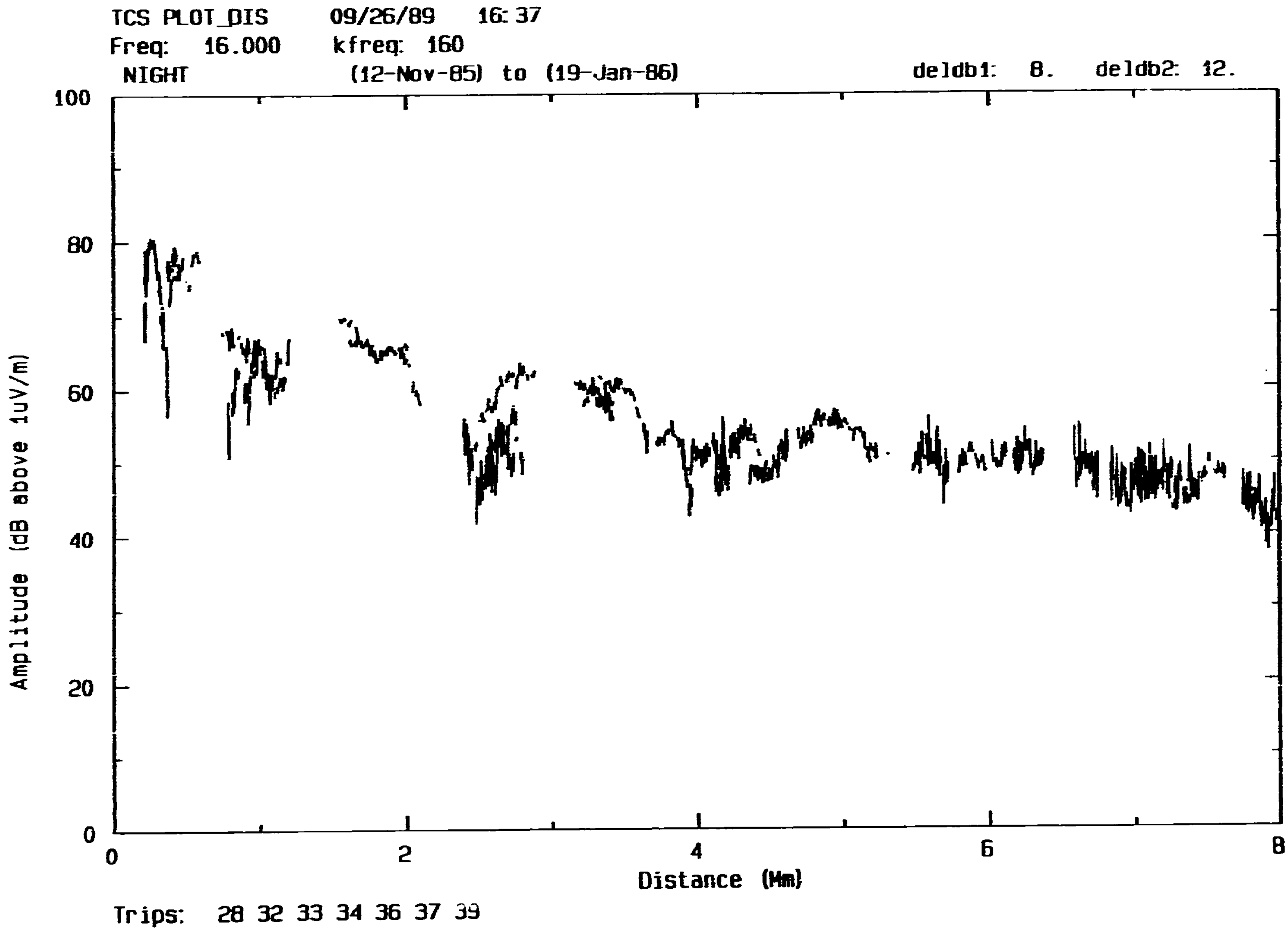


Figure 8. Typical recorded data for Winter season, Rugby at 16.0 kHz.

II-5.3 SOLAR EVENT ANALYSIS

It was recognized that unusual solar activity could have occurred during the Callaghan trips, resulting in ionospheric and/or geomagnetic field disturbances and consequent anomolous signal strength recordings. To investigate this possibility, solar activity records were obtained from the Space Environment Service Center of the National Oceanic and Atmospheric Administration (NOAA) in Boulder, for the periods of the Callaghan trips.

Three solar phenomena are known to affect VLF propagation:

1. Ionization due to X-rays from solar flares (a daytime-only effect).

2. Ionization due to Solar Proton Events (SPEs), which are similar to Polar-Cap Absorption (PCA) events and mostly effect propagation North of 60° N. latitude.

3. Magnetic field disturbances (geomagnetic storms) caused by the flow of solar particles into the earth's magnetosphere, where consequent disturbances are sometimes severe enough to affect the ionosphere. Severe geomagnetic storms often force the auroral zone South of its normal 60° N. position.

Little solar activity was anticipated during the 1985-1986 period of the Callaghan trips, because the solar cycle was near a minimum between the usual eleven-year peaks of activity. Only four SPEs occurred during the trip period, and only three of these coincided with actual trip times. Table 7 lists the start and peak times (again in UT) for applicable SPEs. Because SPE activity was short in each case, no correlation against measured data effects was found.

Only five trips occurred during times of significant geomagnetic storm activity. The five trips, along with relative levels of storm activity are listed in table 8. Storm levels varied from "minor" to "severe" in intensity, where NOAA 24-hour geomagnetic "A Index" levels are defined as:

- Minor Storm: A Index from 30 to 50
- Major Storm: A Index from 50 to 100
- Severe Storm: A Index > 100

Only one severe storm was experienced during the 1985-1986 period, but it occurred during Trip 41, which had been rejected from the primary trip sets at all four frequencies. The other storm levels were judged to be too low and infrequent to correlate with VLF measured data.

Table 7. Solar proton events occurring during Callaghan trips.

TRIP	ORIGIN	DESTINATION	TRIP START		TRIP END		SPE START		SPE PEAK	
4	BAYONNE	BREMERHAVEN	04-24-85	0400	05-02-85	1018	04-25-85	1430	04-26-85	0600
14	SAVANNAH	ALEXANDRIA, EGYPT	07-08-85	0430	07-19-85	0230	07-09-85	0235	07-09-85	0325
40	BAYONNE	CHARLESTON	02-04-86	2330	02-06-86	1118	02-06-86	0825	02-07-86	1730
–	–	–	–	–	–	–	02-14-86	1155	02-15-86	0400

Table 8. Callaghan trips during geomagnetic storms (selected trips in large type).

STORM LEVEL	TRIP	ORIGIN	DESTINATION	START		END	
MAJOR	4	BAYONNE	BREMERHAVEN	04-24-85	0400	05-02-85	1018
MINOR	14	SAVANNAH	ALEXANDRIA, EGYPT	07-08-85	0430	07-19-85	0230
MIN./MAJ.	17	BAYONNE	BREMERHAVEN	08-08-85	0100	08-14-85	2200
MIN./MAJ.	37	JACKSONVILLE, FL	ZEEBRUGGE	12-29-85	0700	01-06-86	1846
SEVERE	41	CHARLESTON	ROTTERDAM	02-08-86	0400	02-18-86	0154

II-5.4 PCAP EVALUATIONS

Figure 2, on page 9, illustrates typical Callaghan trips with respect to the position of the 70° dip angle line (the wide line). Those trips which pass North of Scotland are seen to cross an extensive ocean area North of the line. The 70° dip angle line is also shown on figure 3 with respect to the four signal propagation paths selected for predicted data. Transmissions from the two CONUS sources at 21.4 and 24.0 kHz pass North of the 70° line in the initial portion of their paths. The transmissions from the British transmitters, however, at 16.0 and 19.0 kHz, pass below the 70° line.

The nighttime ionosphere is known to be more depressed in the polar regions, becoming more day-like at the higher latitudes. The LWPC program recognizes this effect by including a polar-cap (PCAP) transition that modifies the $\beta - h'$ model across a user-selectable boundary. The default PCAP setting is 70-74, corresponding to a transition area from 70° to 74° in dip angle. $\beta - h'$ profiles are automatically adjusted for propagation paths passing through the PCAP transition. Table 9 is an example listing of segments along the 60° propagation path from the Annapolis transmitter, where Rho is distance along the path. As the path moves through the area North of the 70° dip angle line, and the codip angle falls below 20° (codip = 90° − dip), a corresponding change is seen in $\beta - h'$. Table 10 lists the Callaghan trips that traversed areas below the 70° dip angle line, and identifies those selected for the primary trip sets at 21.4 and 24.0 kHz.

The Callaghan data is thus a mixed bag from the standpoint of polar-cap effects, and it proved difficult to isolate PCAP-free data. Instead, the project ran LWPC in the default setting (PCAP = 70-74) for all frequencies, then added excursions at 21.4 and 24.0 kHz where PCAP was set at 80-84, thus moving the transition area well above the propagation path areas. Results of the PCAP excursions are presented in the next sections.

Table 9. Path segmentation for Annapolis, path bearing 60°.

RHO	AZIM	CODIP	MAGFLD	SIGMA	EPSR	BETA	HPRIME
0.000	068.0	19.4	0.542	4e+00	81.0	0.39	84.8
0.060	069.1	19.2	0.542	3e−03	15.0	0.39	84.8
0.260	072.8	18.7	0.543	4e+00	81.0	0.39	84.8
0.800	083.1	18.0	0.539	4e−00	81.0	0.38	82.7
1.180	090.0	18.0	0.533	4e+00	81.0	0.39	84.8
2.480	106.5	20.0	0.502	4e+00	81.0	0.41	87.0
5.920	120.0	30.0	0.435	1e−02	15.0	0.41	87.0
6.240	120.8	31.3	0.431	1e−02	15.0	0.41	87.0
6.460	121.4	32.3	0.428	4e+00	81.0	0.41	87.0
7.060	123.1	35.2	0.421	4e−00	81.0	0.41	87.0

Table 10. Callaghan Trips below the 70° dip angle line (large type).

TRIP	ORIGIN	DESTINATION	START		END	
1	*BAYONNE, SC	BREMMERHAVEN	03-29-85	2230	04-08-85	1700
2	*BREMERHAVEN, W. GR.	CHARLESTON	04-11-85	2200	04-19-85	0900
3	CHARLESTON, SC	BAYONNE	04-20-85	0800	04-21-85	0700
4	*BAYONNE	BREMERHAVEN	04-24-85	0400	05-02-85	1018
5	*BREMERHAVEN	BAYONNE	05-05-85	0030	05-13-85	0830
6	*BAYONNE	BREMERHAVEN	05-15-85	0242	05-22-85	0800
7	*BREMERHAVEN	BAYONNE	05-23-85	2100	05-30-85	0800
8	*BAYONNE	BREMERHAVEN	05-31-85	2300	06-07-85	0830
9	*BREMERHAVEN	BAYONNE	06-08-85	2000	06-14-85	2000
10	*BAYONNE	BREMERHAVEN	06-17-85	0400	06-23-85	0800
11	*BREMERHAVEN	BAYONNE	06-25-85	0400	07-01-85	0730
12	BAYONNE	CHARLESTON	07-02-85	0100	07-03-85	0700
13	CHARLESTON	SAVANNAH	07-04-85	0800	07-04-85	0930
14	*SAVANNAH	ALEXANDRIA, EGYPT	07-08-85	0430	07-19-85	0230
15	*ALEXANDRIA	BREMERHAVEN	07-21-85	1400	07-27-85	2130
16	*BREMERHAVEN	BAYONNE	07-29-85	0030	08-04-85	1718
17	*BAYONNE	BREMERHAVEN	08-06-85	0100	08-14-85	2200
18	BREMERHAVEN	ALEXANDRIA	08-16-85	0200	08-22-85	0330
19	*ALEXANDRIA	SAVANNAH	08-25-85	0700	09-08-85	0712
20	*SAVANNAH, GA	BREMERHAVEN	09-10-85	0330	09-18-85	1900
21	*BREMERHAVEN	NORFOLK	09-20-85	2400	09-28-85	2000
22	NORFOLK, VA	CHARLESTON	09-30-85	0119	09-30-85	1900
23	NORFOLK	CHARLESTON	10-23-85	1600	10-24-85	0800
24	*CHARLESTON	ROTTERDAM, HOLLAND	10-28-85	1300	11-01-85	1700
25	ROTTERDAM	LIVERPOOL	11-03-85	1445	11-04-85	2000
26	LIVERPOOL, ENGLAND	ANTWERP	11-06-85	1534	11-07-85	1722
27	ANTWERP, BELGIUM	BREMERHAVEN	11-08-85	2400	11-09-85	0830
28	*BREMERHAVEN	CHARLESTON	11-12-85	0300	11-21-85	0830
29	CHARLESTON	BAYONNE	11-22-85	0800	11-23-85	1100
30	BAYONNE	NORFOLK	11-28-85	0130	11-30-85	1000
31	NORFOLK	SAVANNAH	12-01-85	2300	12-02-85	1830
32	SAVANNAH	CRISTOBAL, PANAMA	12-05-85	1430	12-08-85	0641
33	CRISTOBAL	SAVANNAH	12-10-85	1740	12-13-85	0630
34	SAVANNAH	PUERTO CORTEZ, HONDURAS	12-17-85	0200	12-19-85	1122
35	NO DATA					
36	CRISTOBAL	JACKSONVILLE	12-23-85	2214	12-28-85	1100
37	*JACKSONVILLE, FL	ZEEBRUGGE	12-29-85	0700	01-06-86	1846
38	ZEEBRUGGE, BELGIUM	BREMERHAVEN	01-08-86	0654	01-08-86	1925
39	*BREMERHAVEN	BAYONNE	01-10-86	2300	01-19-86	1900
40	BAYONNE	CHARLESTON	02-04-86	2330	02-09-86	1118
41	CHARLESTON	ROTTERDAM	02-08-86	0400	02-16-86	0154
42	NO DATA					
43	*BREMERHAVEN	BEAUMONT	02-22-86	0600	03-04-86	0718
44	BEAUMONT, TX	CHARLESTON	03-07-86	1830	03-08-86	0918
45	*CHARLESTON	ROTTERDAM	03-09-86	0800	03-16-86	0500
46	ROTTERDAM	BOGEN, NORWAY	03-18-86	0300	03-20-86	1000
47	*BOGEN	MOREHEAD CITY NC	03-24-86	0018	04-02-86	1300
48	MOREHEAD CITY	CHARLESTON	04-05-86	0015	04-05-86	0900
49	CHARLESTON	BAYONNE	04-06-86	0800	04-07-86	0830
50	*BAYONNE	ROTTERDAM	04-08-86	0100	04-15-86	0800
51	ROTTERDAM	BREMERHAVEN	04-16-86	0230	04-16-86	1101
52	*BREMERHAVEN	BAYONNE	04-18-86	0100	04-25-86	1700

*Indicates trips selected for Primary Trip Sets at 21.4 and 24.0 kHz.

SECTION II-6

PREDICTED VS. MEASURED DATA COMPARISONS

II-6.1 RUGBY, 16.0 kHz

Primary results of the analysis are presented in this and the following sections. As was described in the methodology discussion of section II-2, PLOT_DIS amplitude vs. distance plots of aggregated data from the Callaghan recordings are compared with overlays of predicted data graphed to the same scale. Figures 9-38 are plots of such data arranged as recorded and predicted pairs, with the measurements and predictions shown as a function of distance from the transmitter along great circle paths. All data is for nighttime, extracting trip data satisfying the criteria that both the transmitter and receiver (ship) locations have solar zenith angles greater than 90°.

Graphs for the Rugby transmitter at 16.0 kHz are given in figures 9-13, which are illustrative of the many comparisons made during the analysis. Because of the great volume of such graphs generated by the project, only representative samples are presented in this report. A common format is used for all frequency sections, where the first graph compares recorded data with the LWPC default-setting prediction. A sequence of four additional comparisons then follows, illustrating a different β selection spread over four values of h′. The discussions of section II-7.7 explain how summary graphs were used to verify β−h′ profile recommendations for the overall frequency range.

The 16-kHz examples of this section indicate how the recorded vs. predicted data fit was improved by increasing β and decreasing h′ with respect to the LWPC default settings. The comparisons concentrate on the distance ranges between zero and five megameters in searching for best data fits. It is possible to improve the fit in the extreme far field (5-8 Mm) by increasing β substantially, but the close-in curves no longer match as well and the selection becomes suspect. Constraint of the data-fit selection to distances <5 Mm is justified because, beyond that range, the measured data is less reliable as recorded levels approach those of atmospheric and shipboard noise.

In each of the figures, applicable trip numbers are shown below the lower edge of the graph. The predicted data file noted above the graph gives a two-character run code, then the letters "as" denoting the LWPC ASCII output file, followed by the β−h′ designation. For example, the notation of figure 9 shows that "Run fc" was for a β range of 0.30 to 0.80 (corresponding to a 10- to 60-kHz frequency range) and was for an h′ of 87 km.

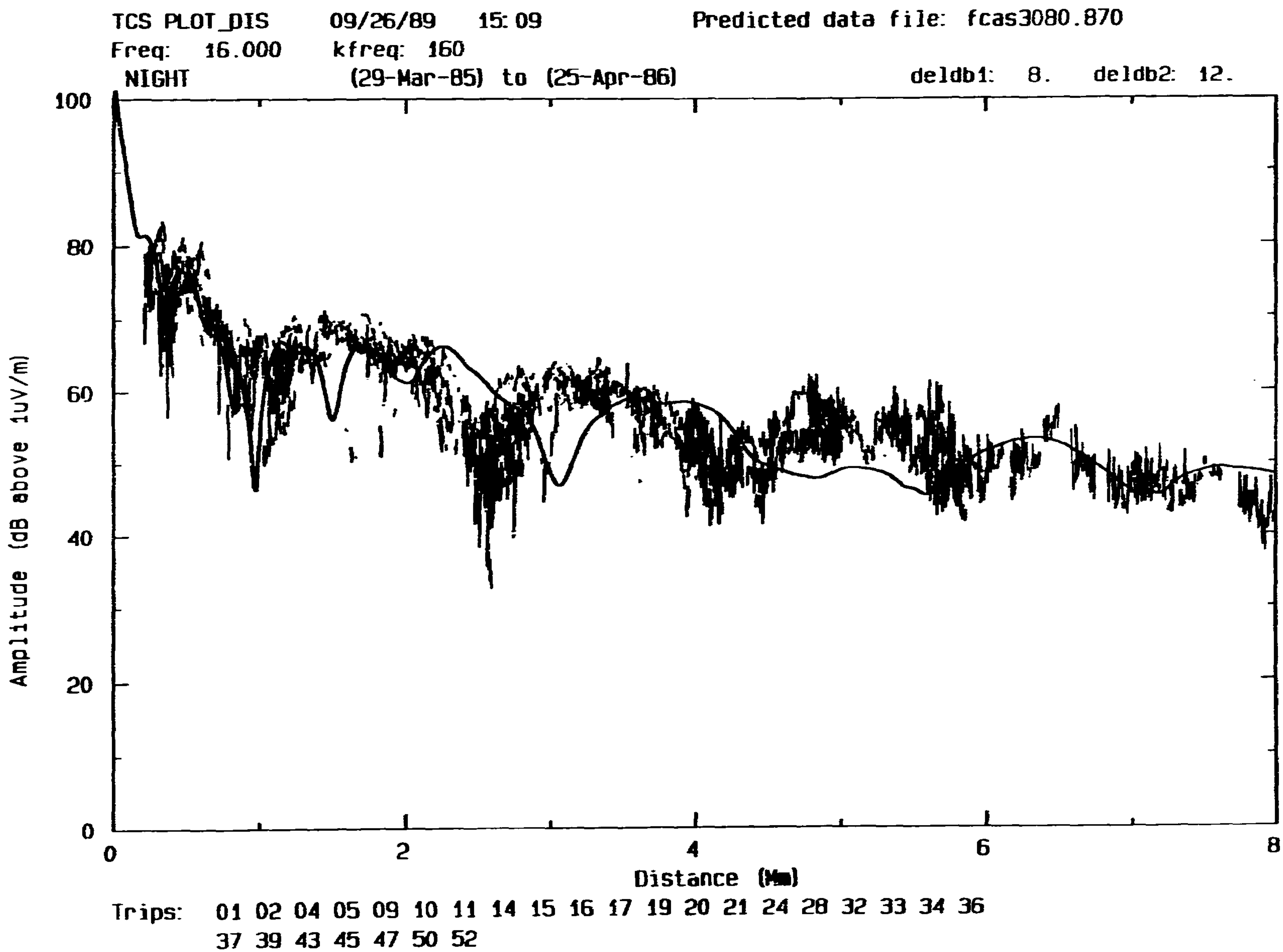


Figure 9. LWPC prediction for $\beta = 0.36$, $h' = 87$ (default), PCAP = 70-74, with recorded data for Rugby at 65 kW, 16.0 kHz.

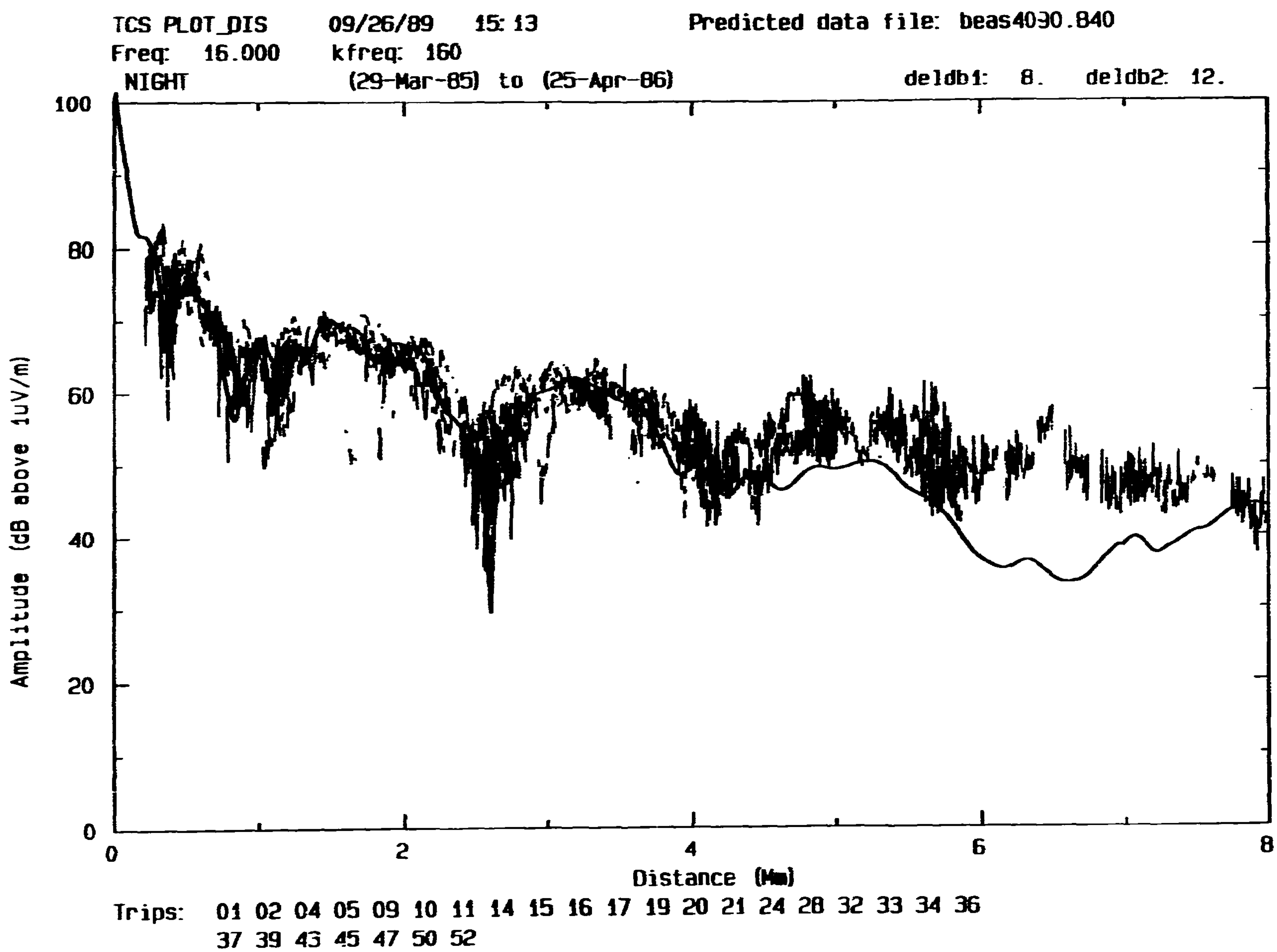


Figure 10. LWPC prediction for $\beta=0.46$, $h'=84$, PCAP=70-74, with recorded data for Rugby at 65 kW, 16.0 kHz.

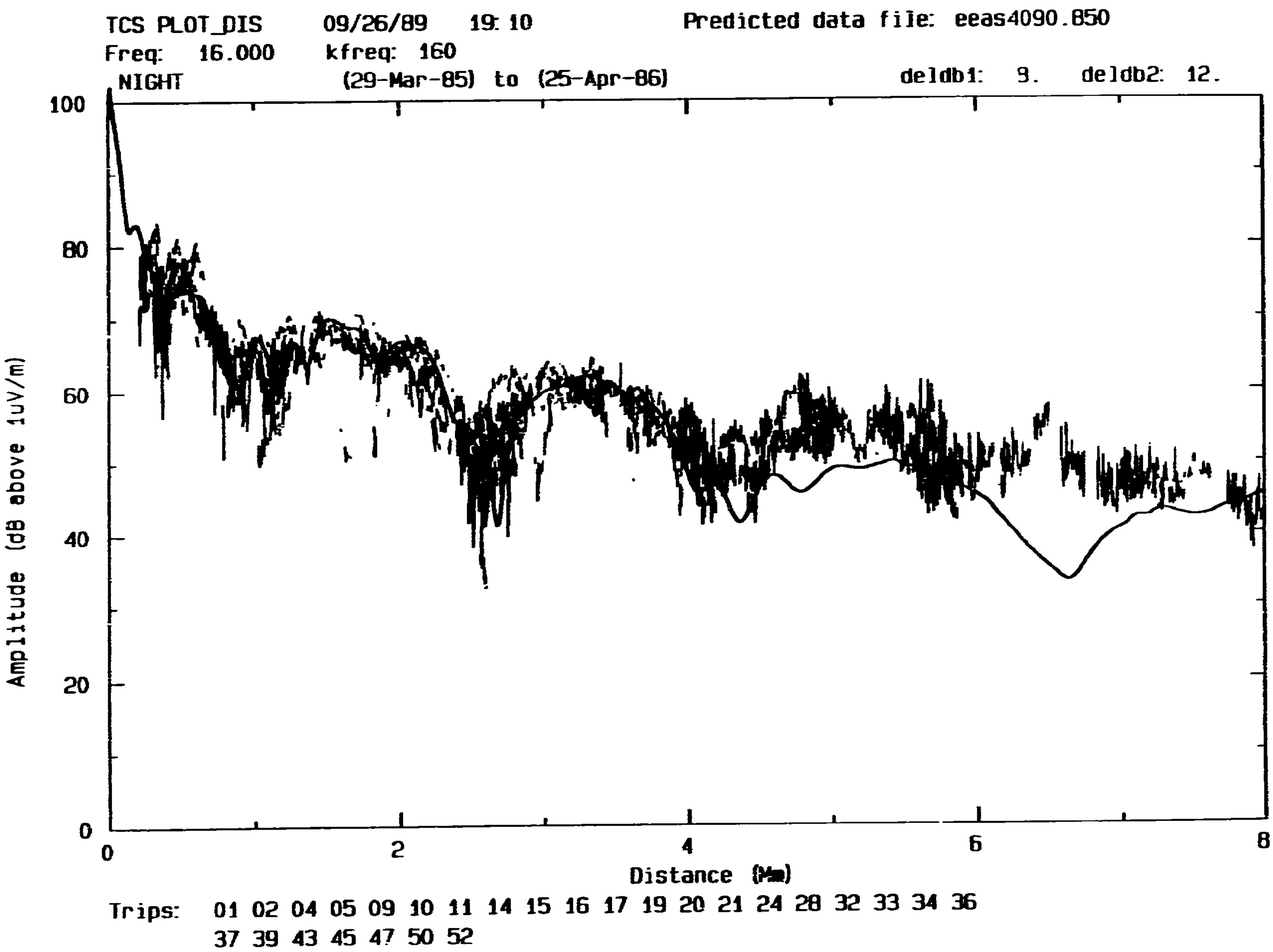


Figure 11. LWPC prediction for $\beta=0.46$, $h'=85$, PCAP=70-74, with recorded data for Rugby at 65 kW, 16.0 kHz.

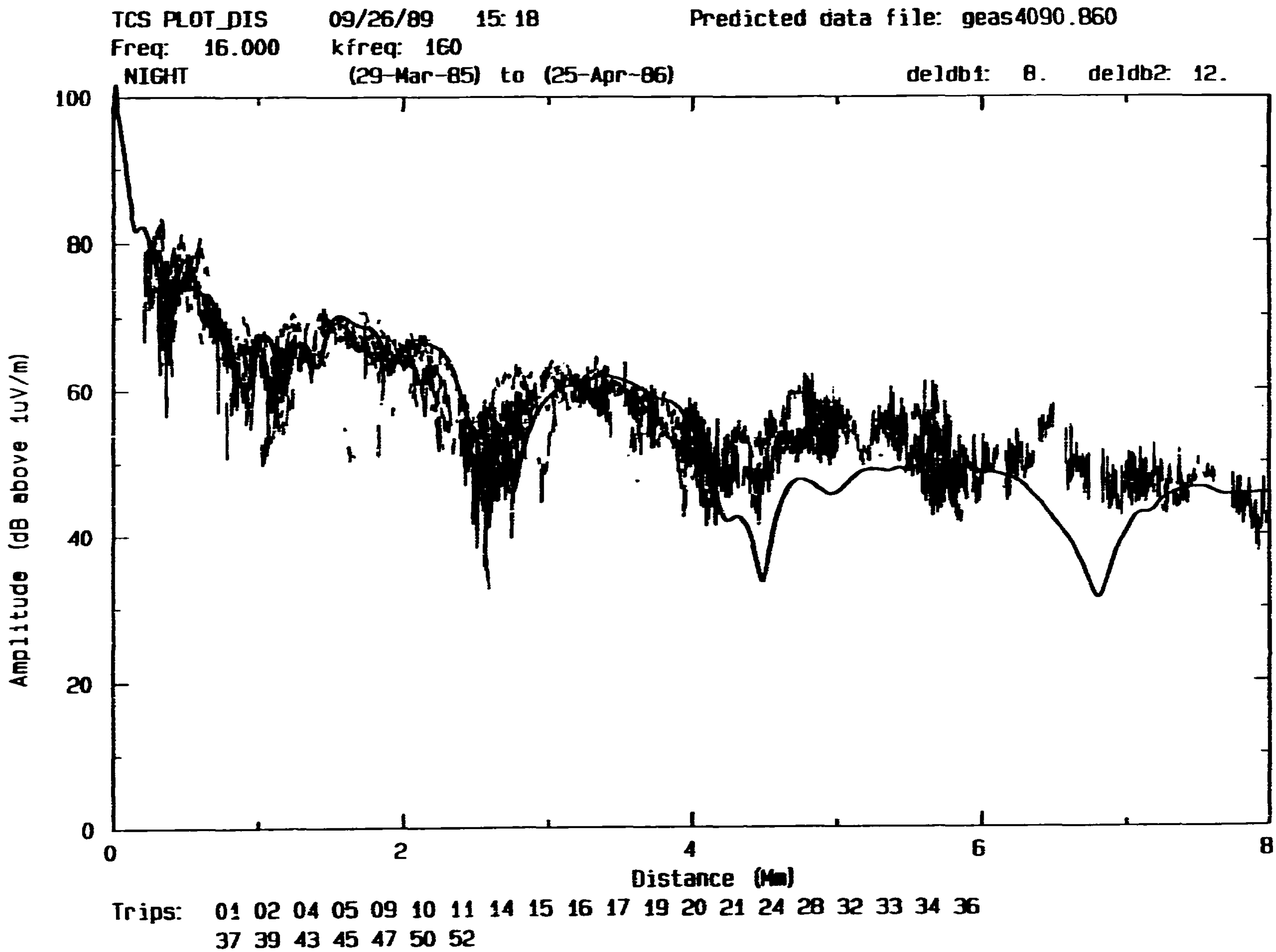


Figure 12. LWPC prediction for $\beta=0.46$, $h'=86$, PCAP=70-74, with recorded data for Rugby at 65 kW, 16.0 kHz.

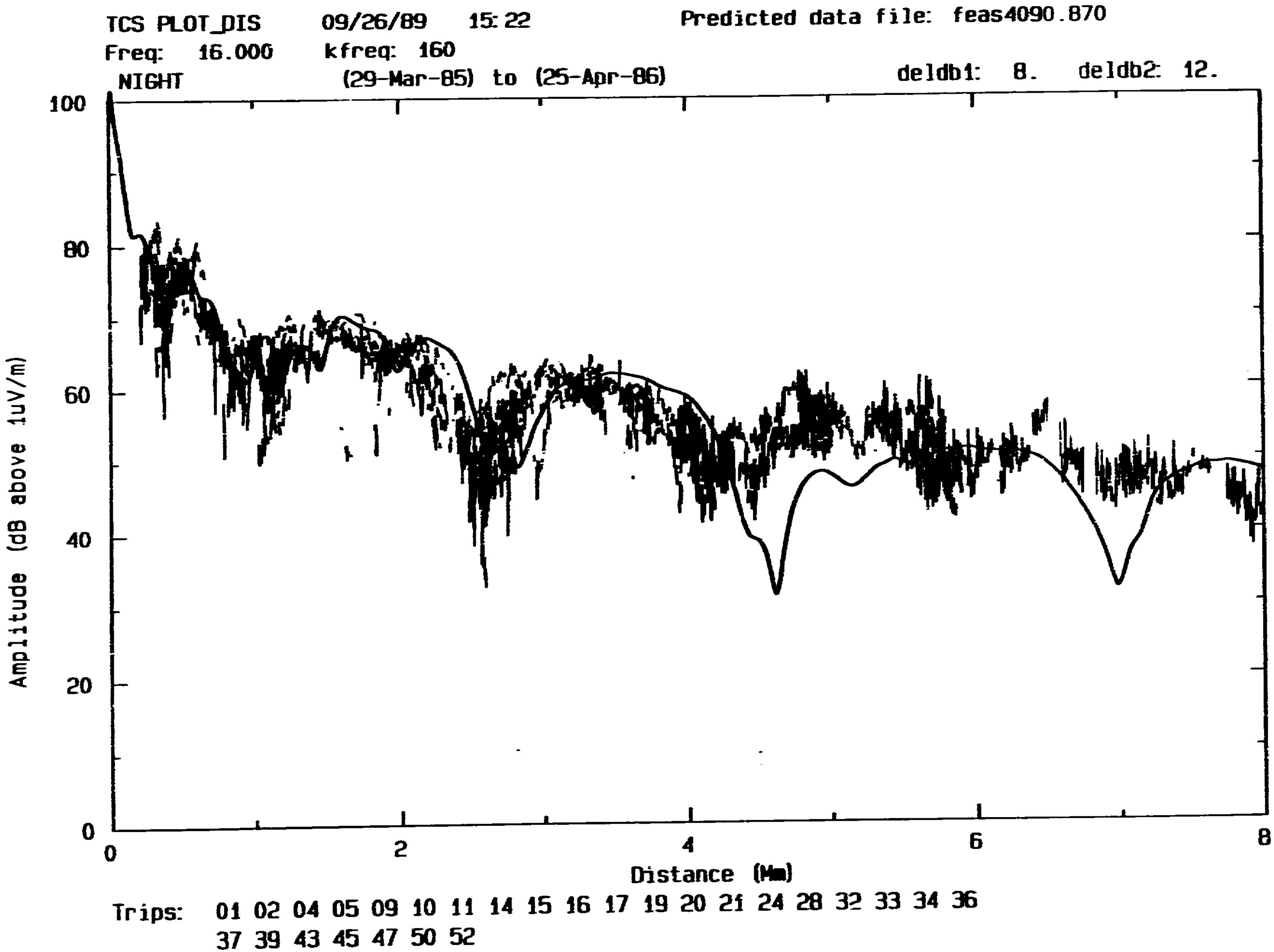


Figure 13. LWPC prediction for $\beta=0.46$, $h'=87$, PCAP=70-74, with recorded data for Rugby at 65 kW, 16.0 kHz.

II-6.2 ANTHORNE, 19.0 kHz

Results for the 19.0-kHz transmitter are shown in figures 14-18. As was the case for 16 kHz, the default profile shows the longer "cycles" between fades when compared with measured data, indicating that a change to a lower h′ is in order. This is confirmed in figures 15-18, where β was adjusted, also.

β is increased to the 0.40-0.90 range in this instance. With interpolation by the LWPC, a β of 0.49 was selected by the computer for this frequency.

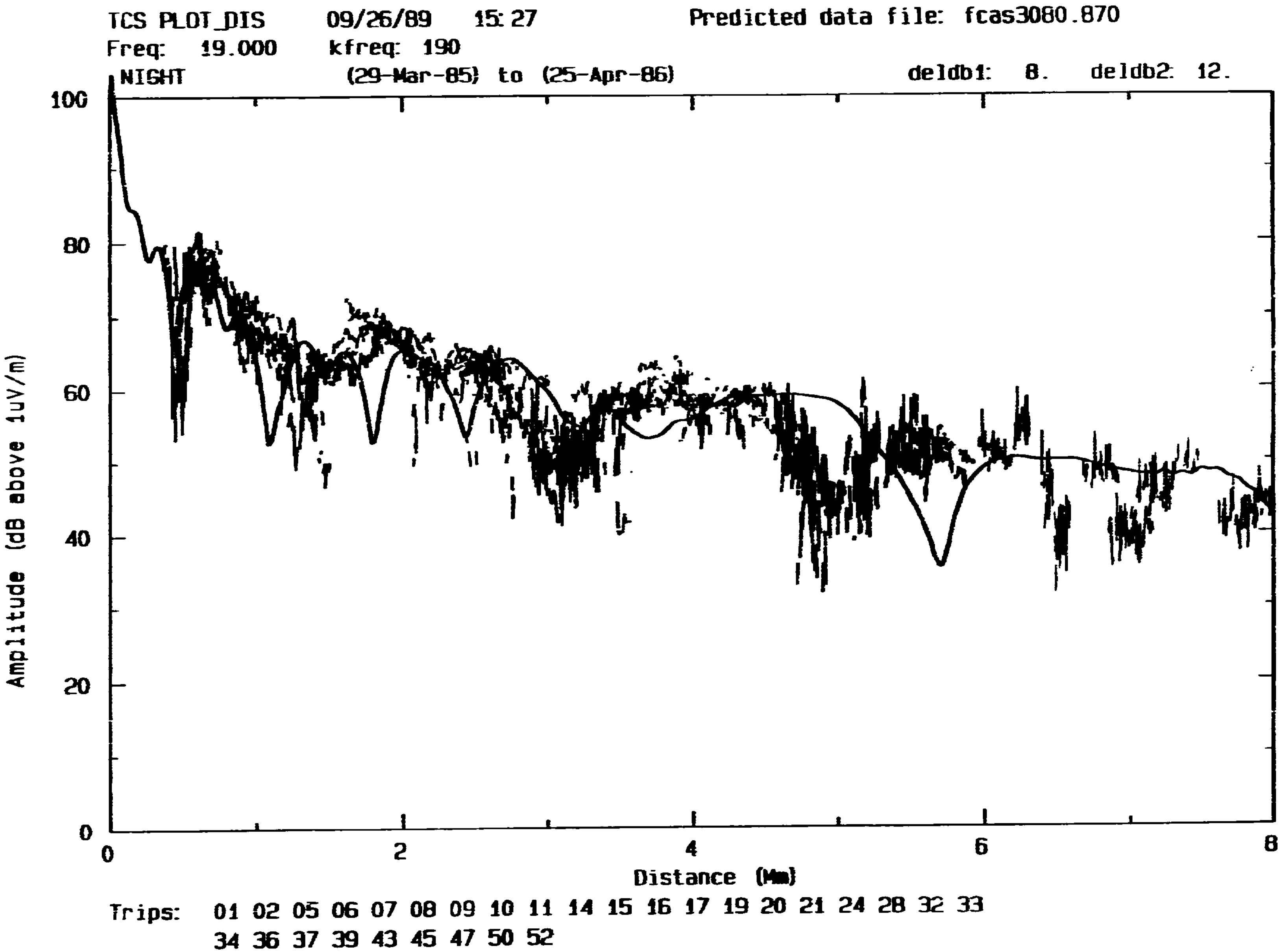


Figure 14. LWPC prediction for $\beta=0.39$, $h'=87$ (default), PCAP=70-74, with recorded data for Anthorne at 80 kW, 19.0 kHz.

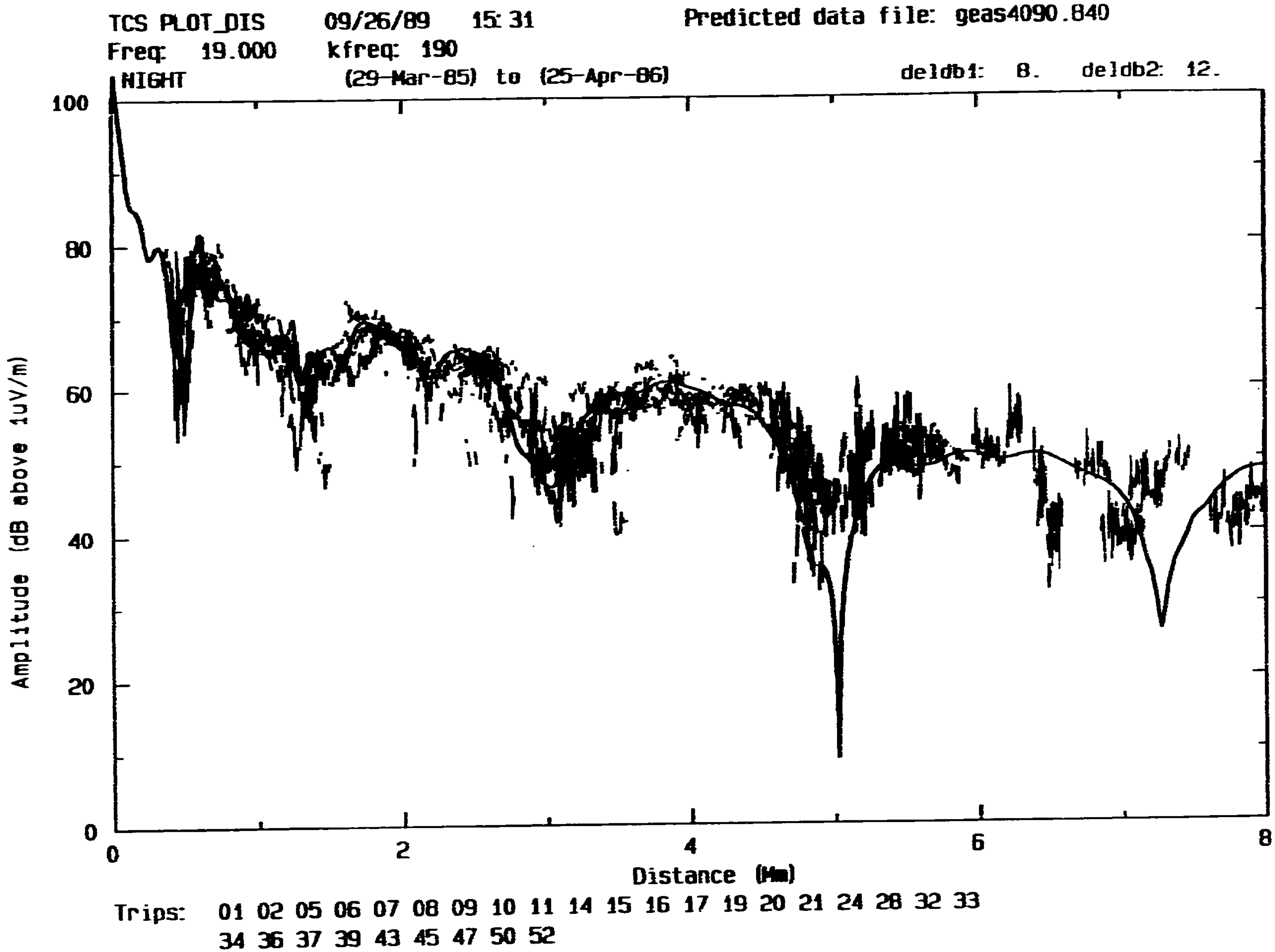


Figure 15. LWPC prediction for $\beta=0.49$, $h'=84$, PCAP=70-74, with recorded data for Anthorne at 80 kW, 19.0 kHz.

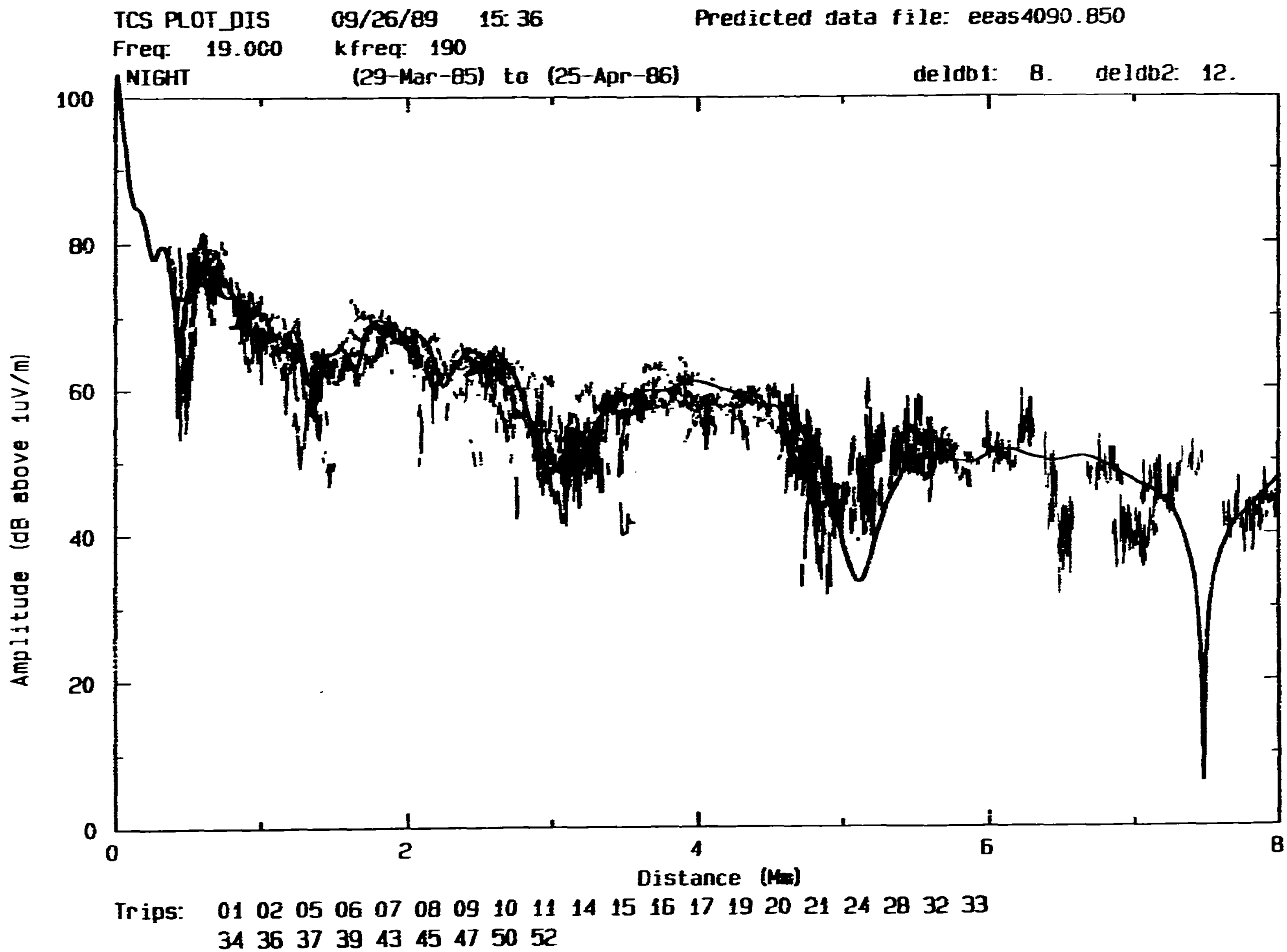


Figure 16. LWPC prediction for $\beta=0.49$, $h'=85$, PCAP=70-74 with recorded data for Anthorne at 80 kW, 19.0 kHz.

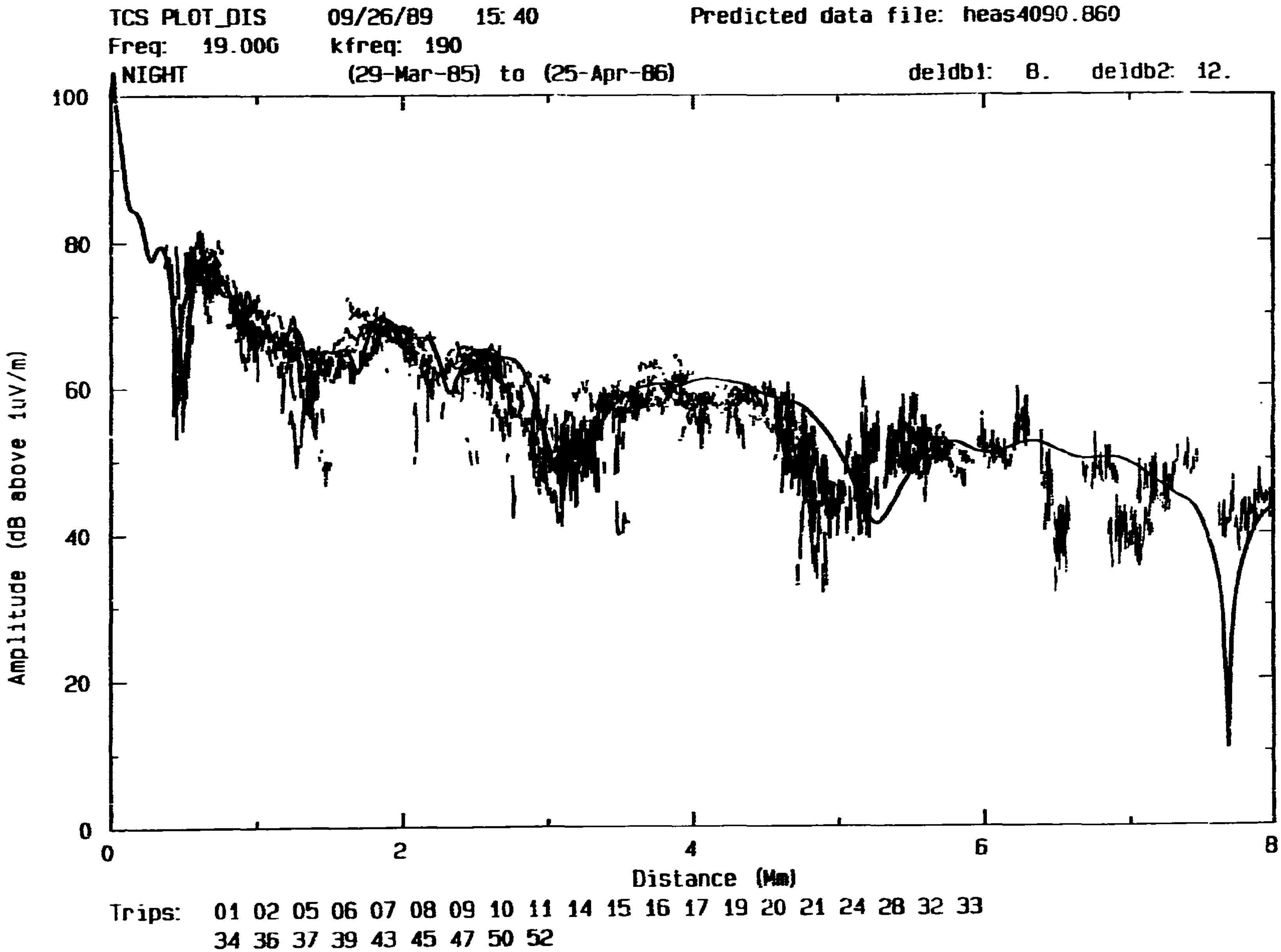


Figure 17. LWPC prediction for $\beta=0.49$, $h'=86$, PCAP=70-74, with recorded data for Anthorne at 80 kW, 19.0 kHz.

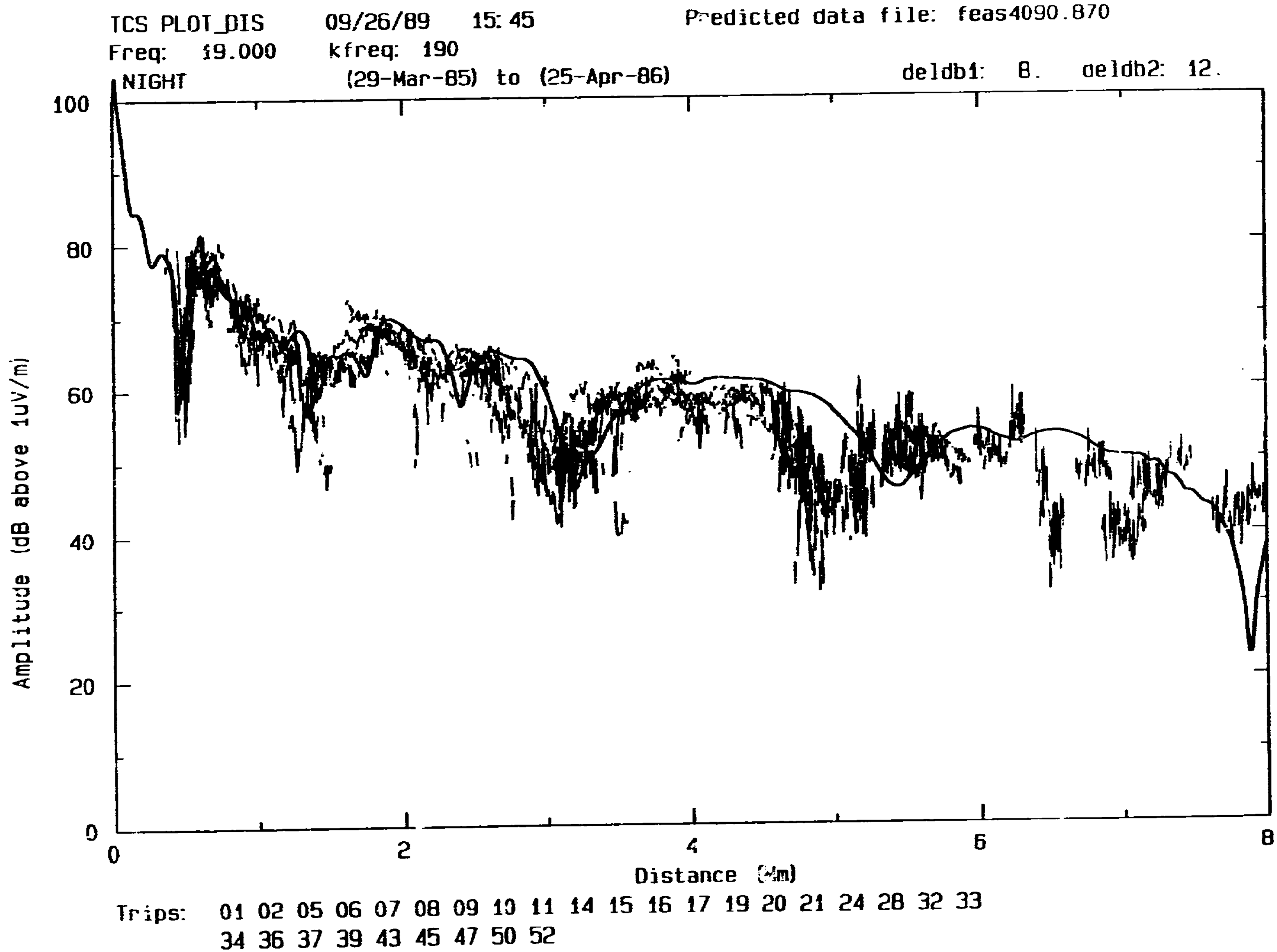


Figure 18. LWPC prediction for $\beta = 0.49$, $h' = 87$, PCAP = 70-74, with recorded data for Anthorne at 80 kW, 19.0 kHz.

II-6.3 ANNAPOLIS, 21.4 kHz

As frequency increases, wavelength shortens and the earth-ionosphere waveguide can support many more propagation modes. This is confirmed by the added complexity of both measured and predicted data at 21.4 kHz. when compared with the similar curves of the lower frequencies.

The default LWPC profile shown in figure 19 reflects the addition of higher-order modes, but lacks the deep fading patterns suggested by the first two nulls of the measured data. These nulls are restored in the $\beta = 0.51$ profiles of figures 20-23, but the selection of the best h′ has become more difficult and subjective at this higher frequency.

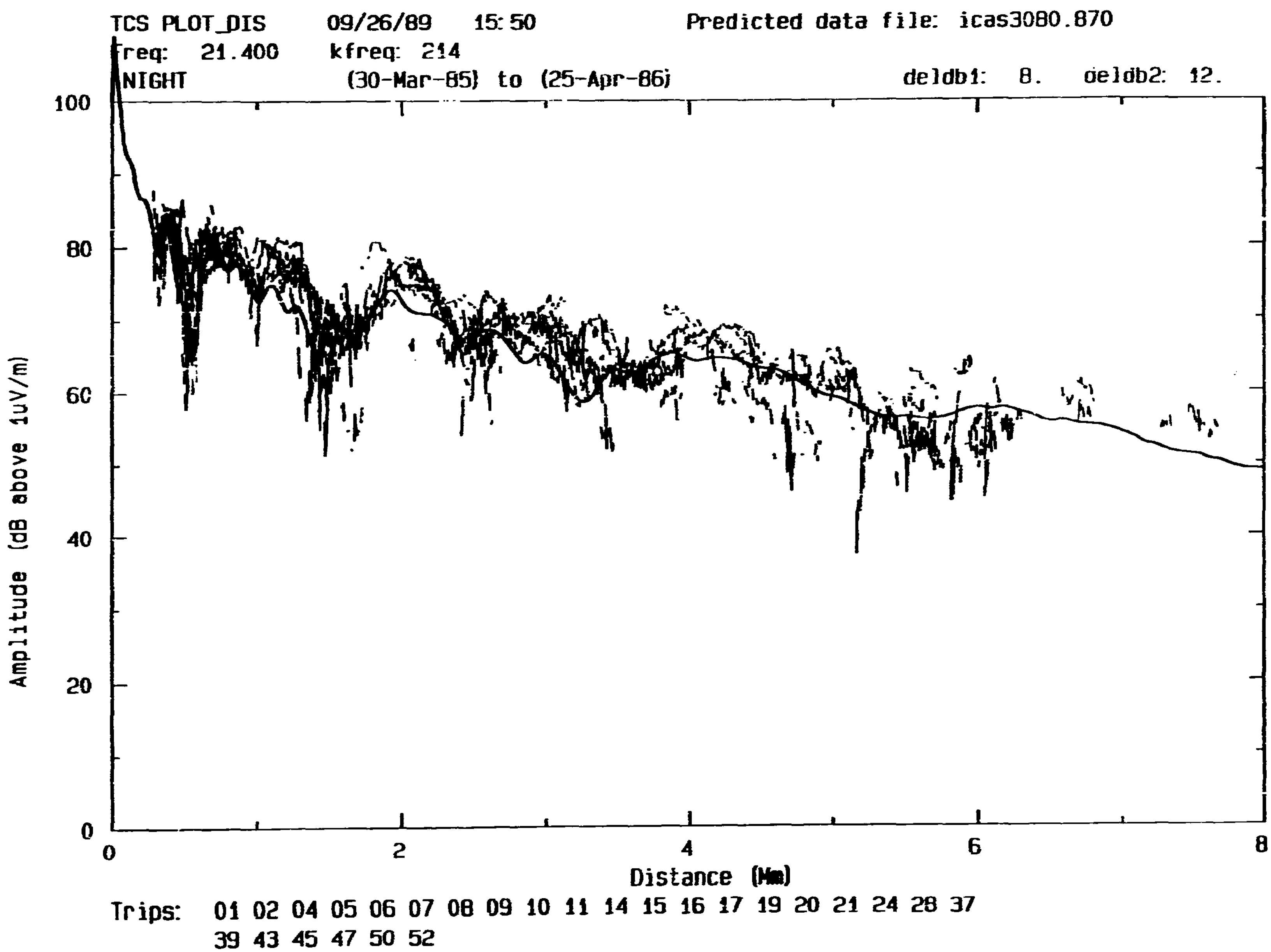


Figure 19. LWPC prediction for $\beta=0.41$, $h'=87$ (default), PCAP=70-74, with recorded data for Annapolis at 250 kW, 21.4 kHz.

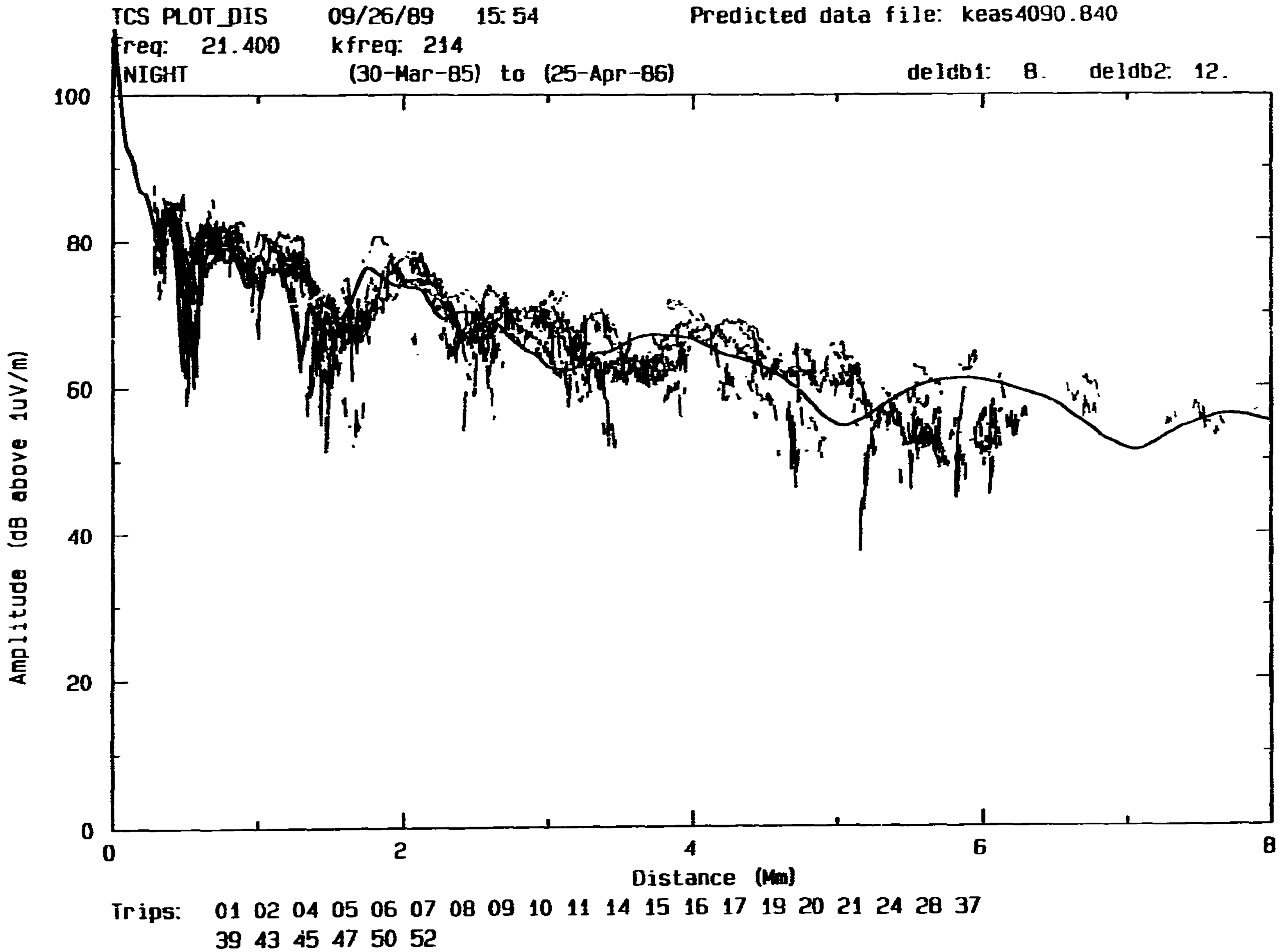


Figure 20. LWPC prediction for $\beta=0.51$, $h'=84$, PCAP=70-74, with recorded data for Annapolis at 250 kW, 21.4 kHz.

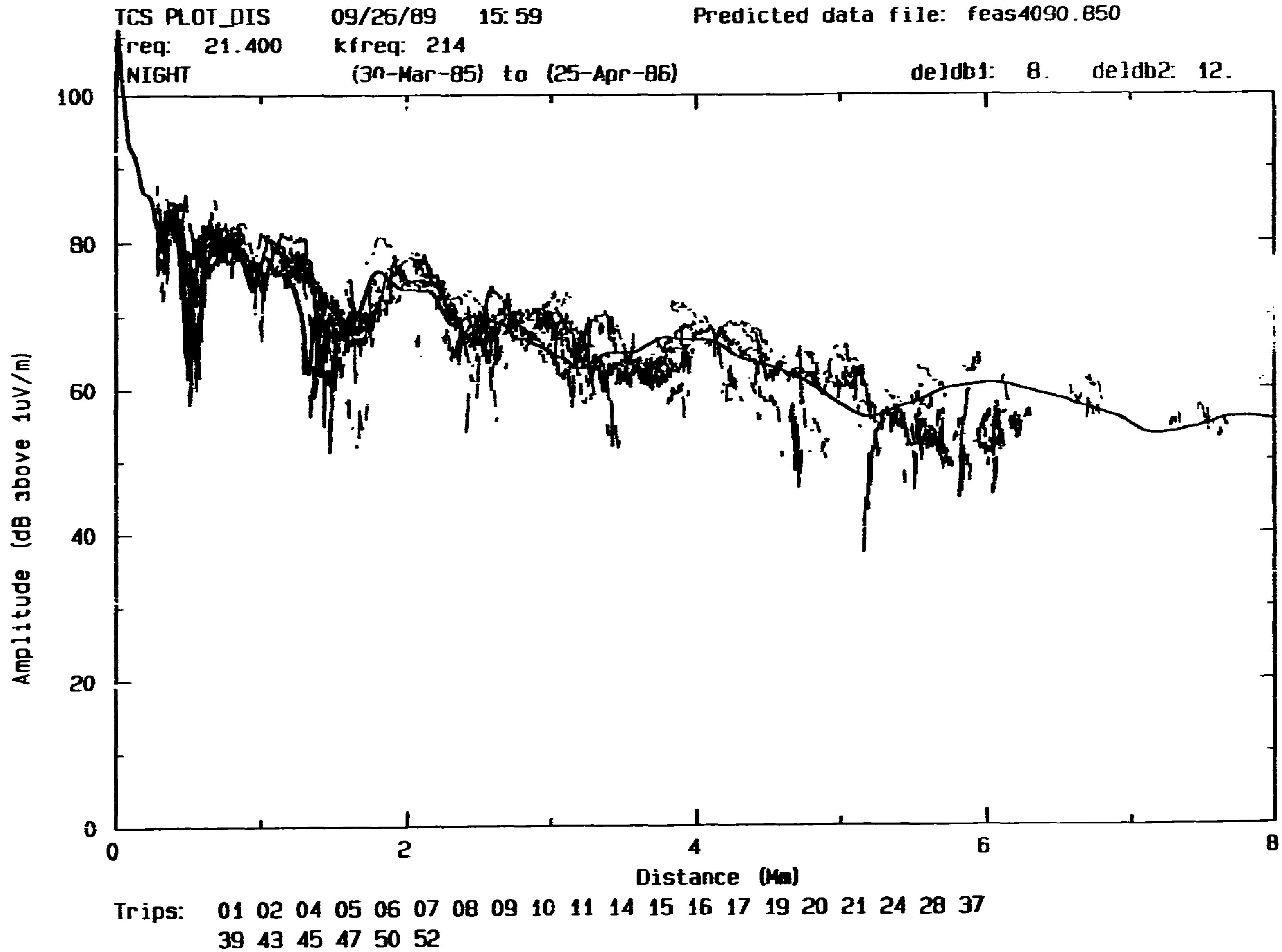


Figure 21. LWPC prediction for $\beta=0.51$, $h'=85$, PCAP=70-74, with recorded data for Annapolis at 250 kW, 21.4 kHz.

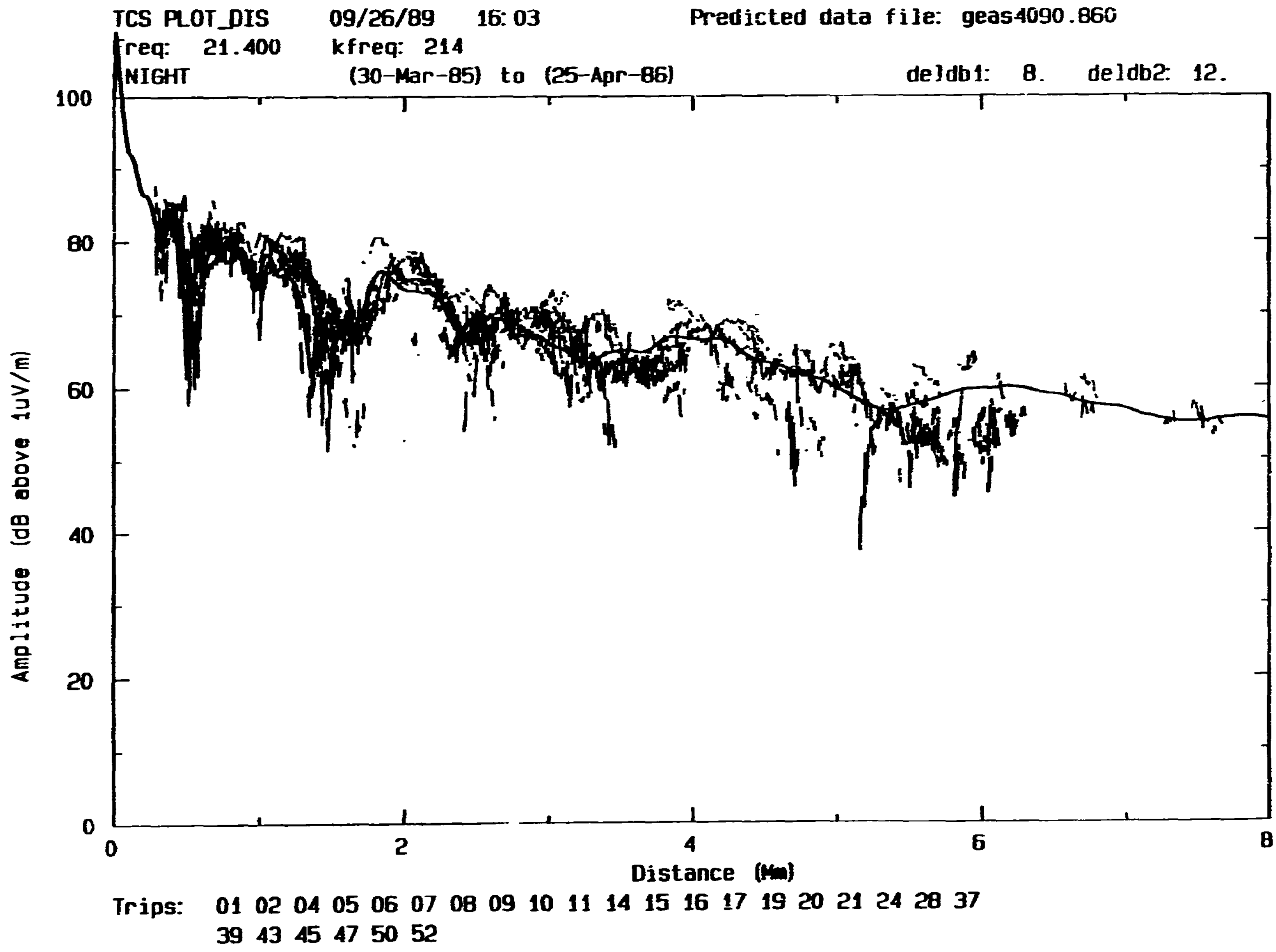


Figure 22. LWPC prediction for $\beta=0.51$, $h'=86$, PCAP=70-74, with recorded data for Annapolis at 250 kW, 21.4 kHz.

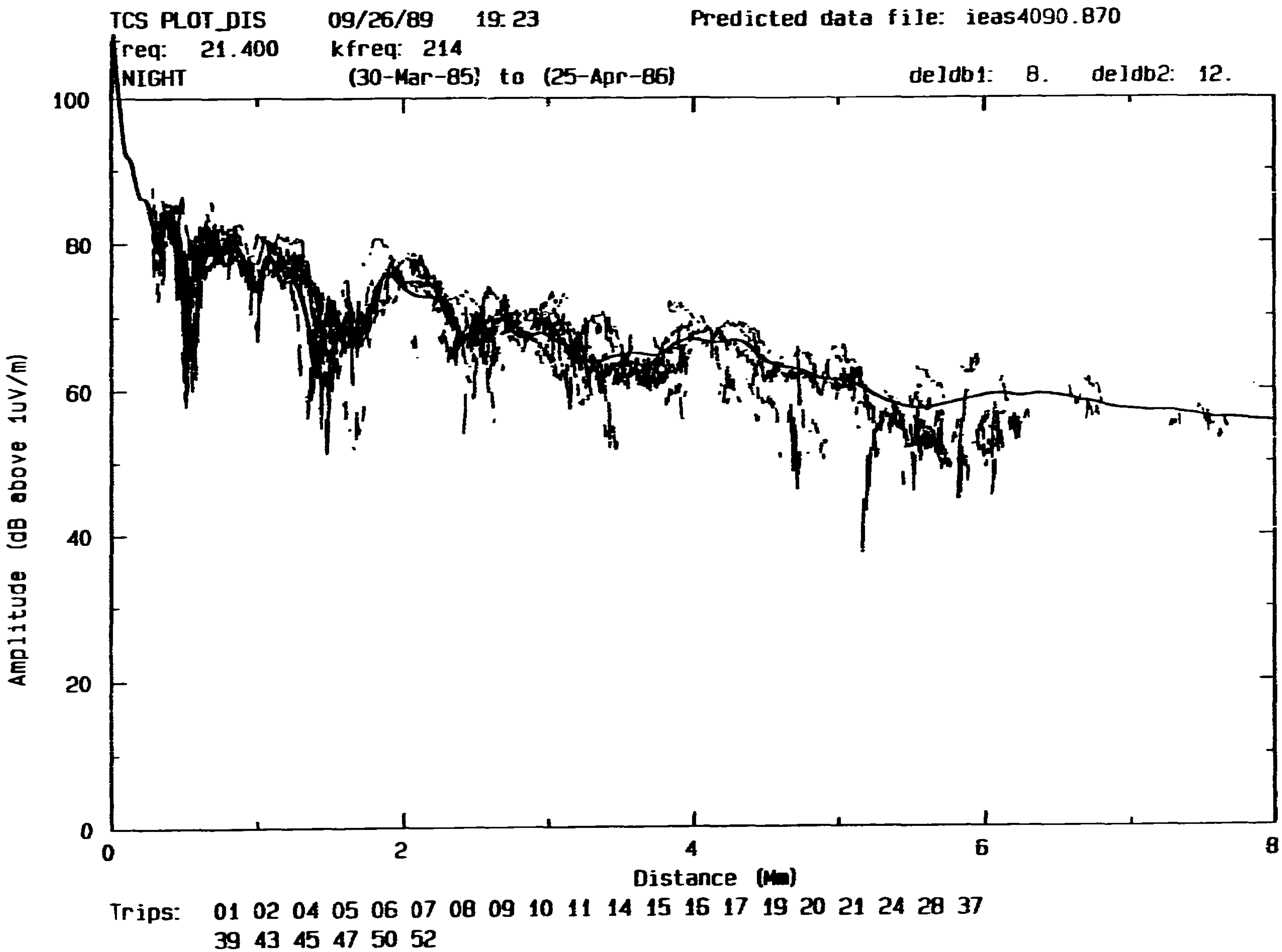


Figure 23. LWPC prediction for $\beta=0.51$, $h'=87$, PCAP=70-74, with recorded data for Annapolis at 250 kW, 21.4 kHz.

II-6.4 CUTLER, 24.0 kHz

The default LWPC prediction of figure 24 shows even more high-order mode effects than in the 21.4-kHz case. Again, the nulls seem less pronounced than in the measured data.

Selection of a higher β range, as in figures 25-28, results in a partial improvement, but the match of fading positions is disappointing. This sequence suggests the need for automation of the selection process so that many more profiles may be examined within practical time constraints. Mechanization of the comparisons is discussed in section II-7.7.

The predicted curves shown thus far in the figures utilized the LWPC default polar-cap settings (see discussion in section II-5.4). As a further point of interest, PCAP adjustments were eliminated in the excursions of the following sections.

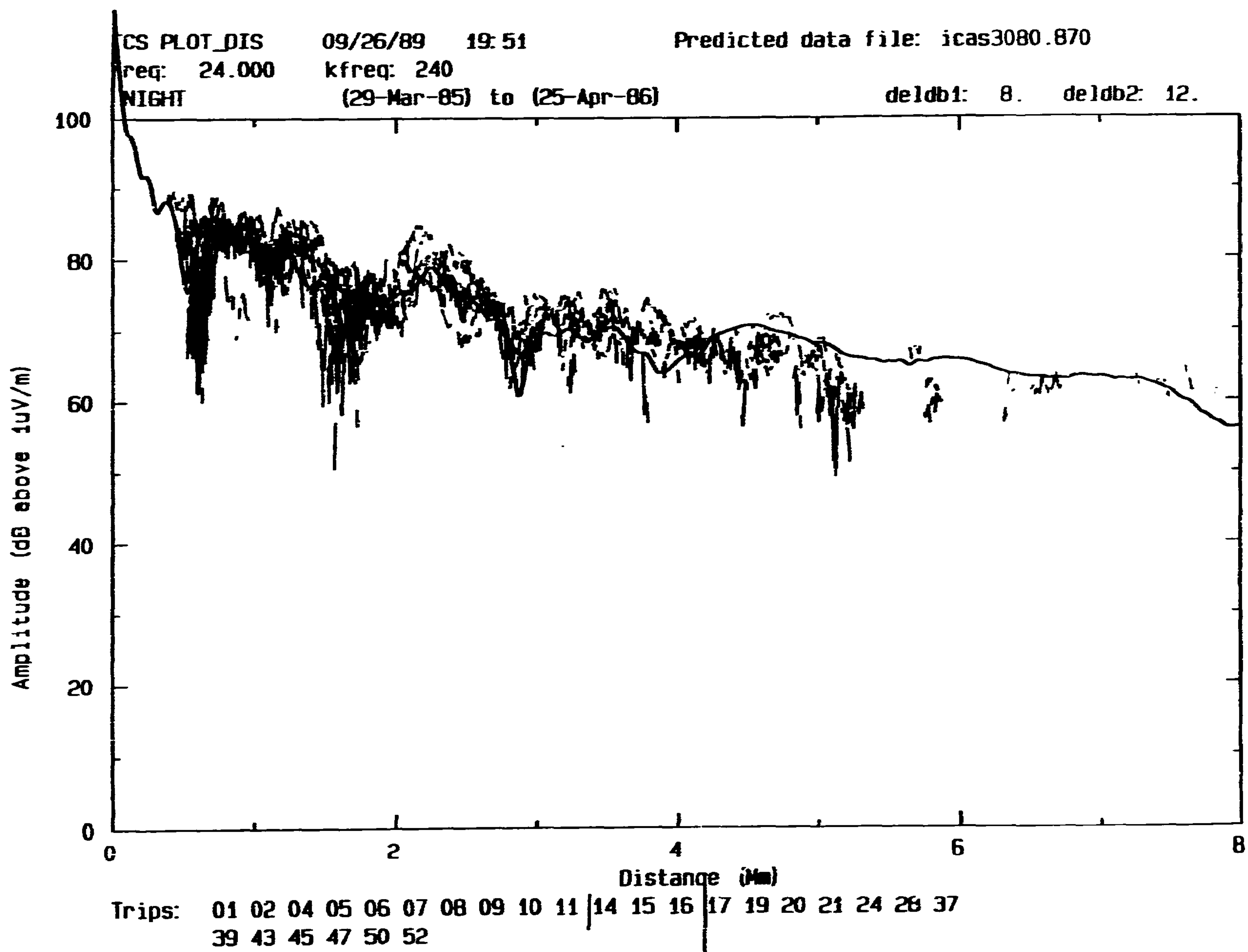


Figure 24. LWPC prediction for $\beta=0.44$, $h'=87$ (default), PCAP=70-74, with recorded data for Cutler at 1000 kW, 24.0 kHz.

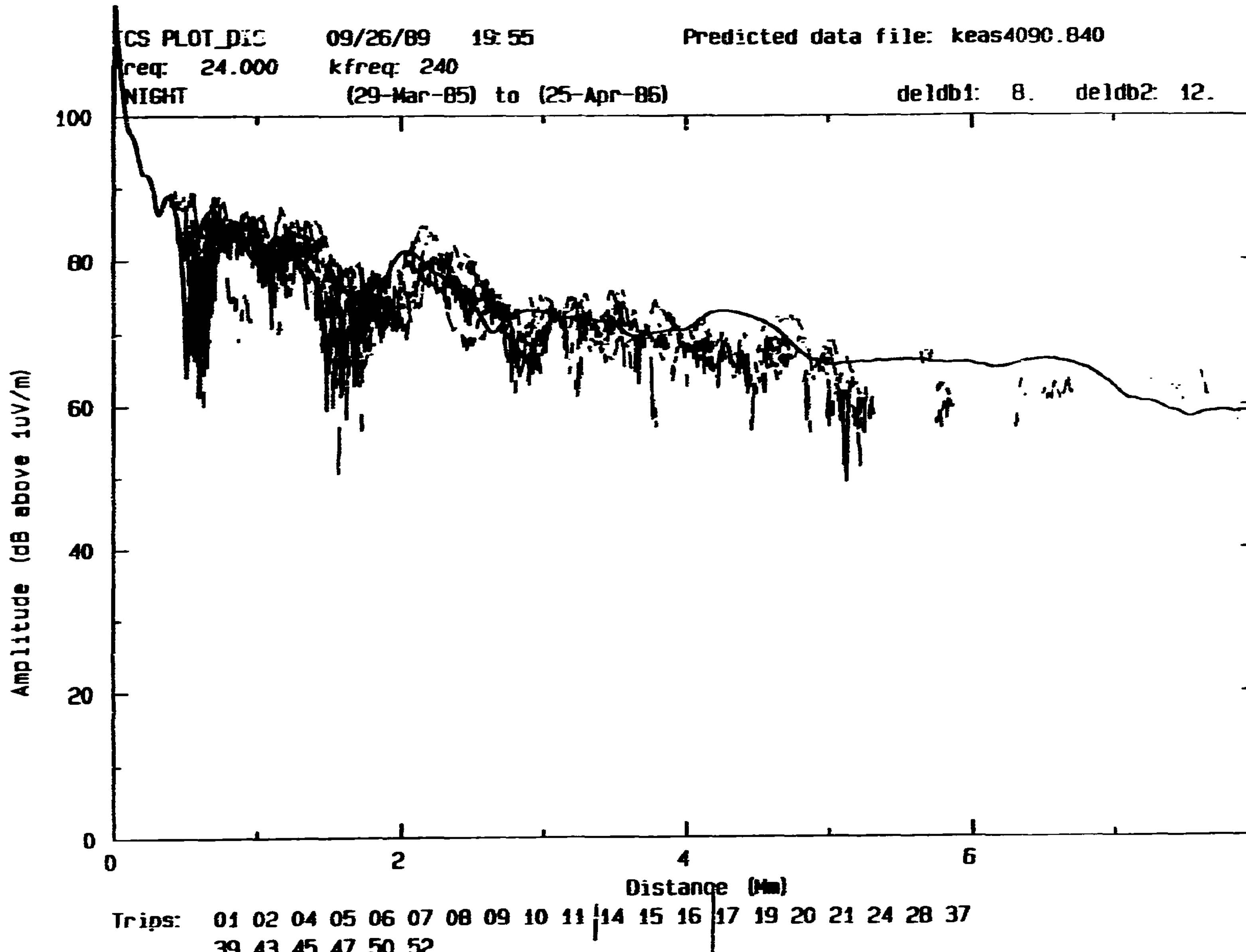


Figure 25. LWPC prediction for $\beta = 0.54$, $h' = 84$, PCAP=70-74, with recorded data for Cutler at 1000 kW, 24.0 kHz.

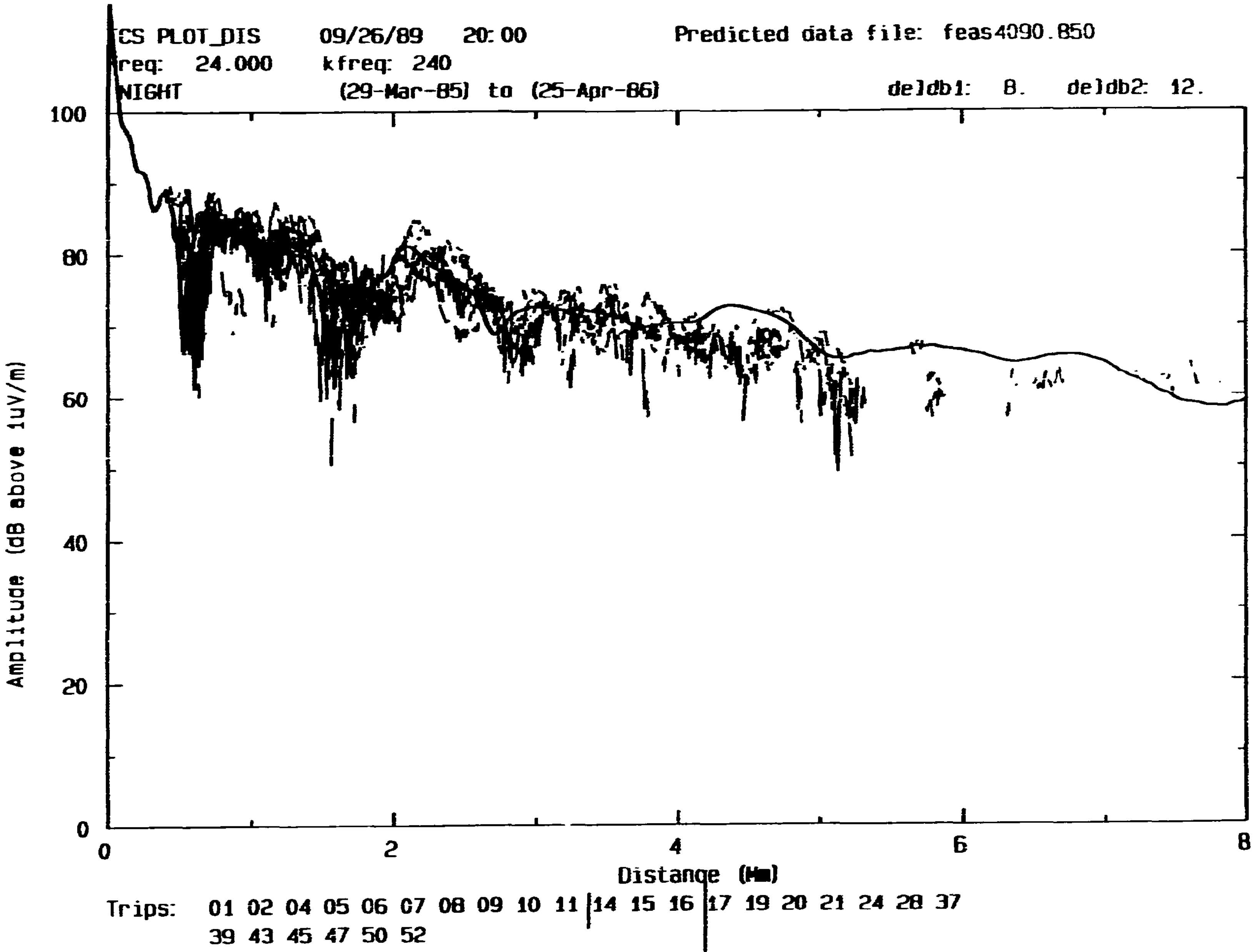


Figure 26. LWPC prediction for $\beta=0.54$, h′=85, PCAP=70-74, with recorded data for Cutler at 1000 kW, 24.0 kHz.

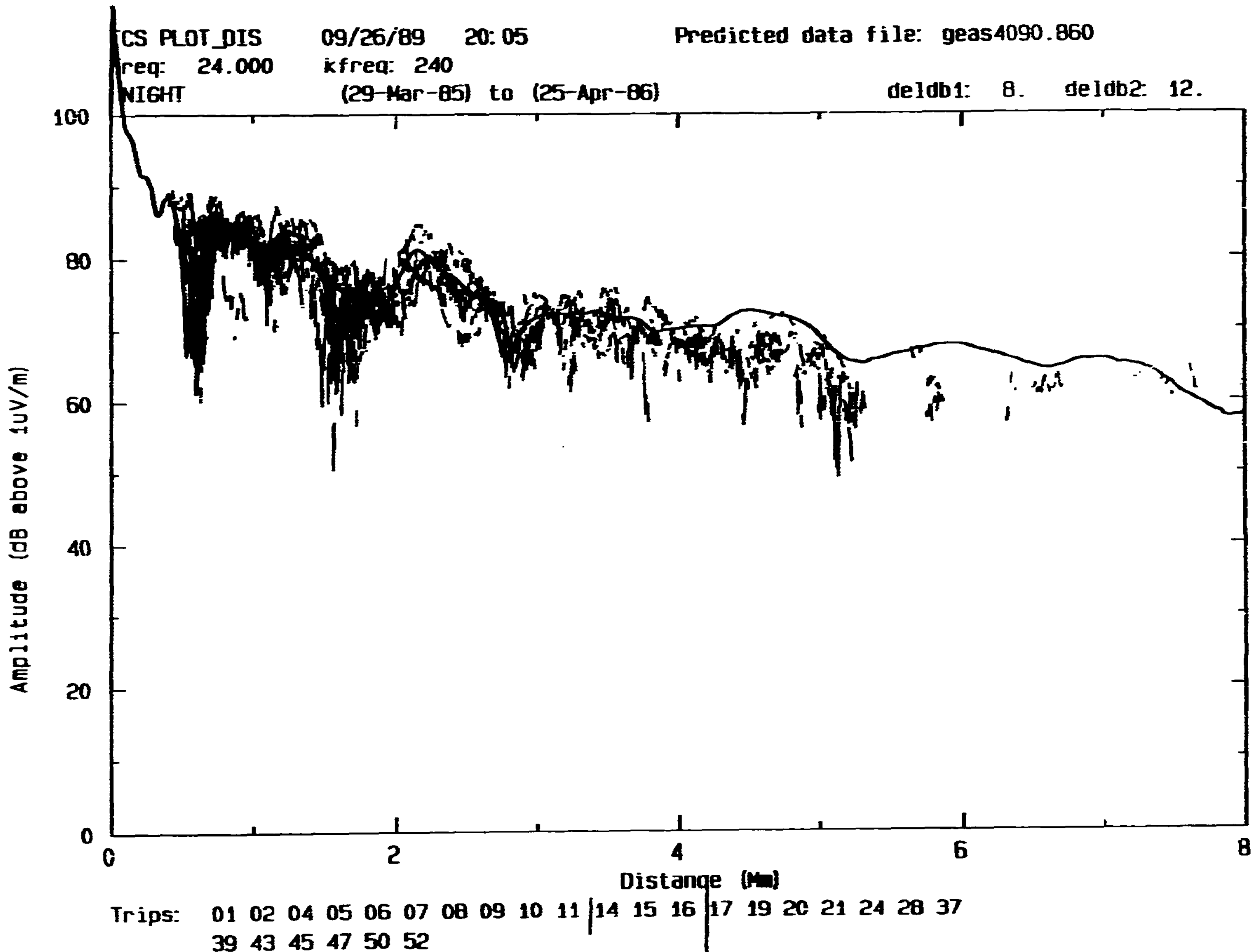


Figure 27. LWPC prediction for $\beta=0.54$, $h'=86$, PCAP=70-74, with recorded data for Cutler at 1000 kW, 24.0 kHz.

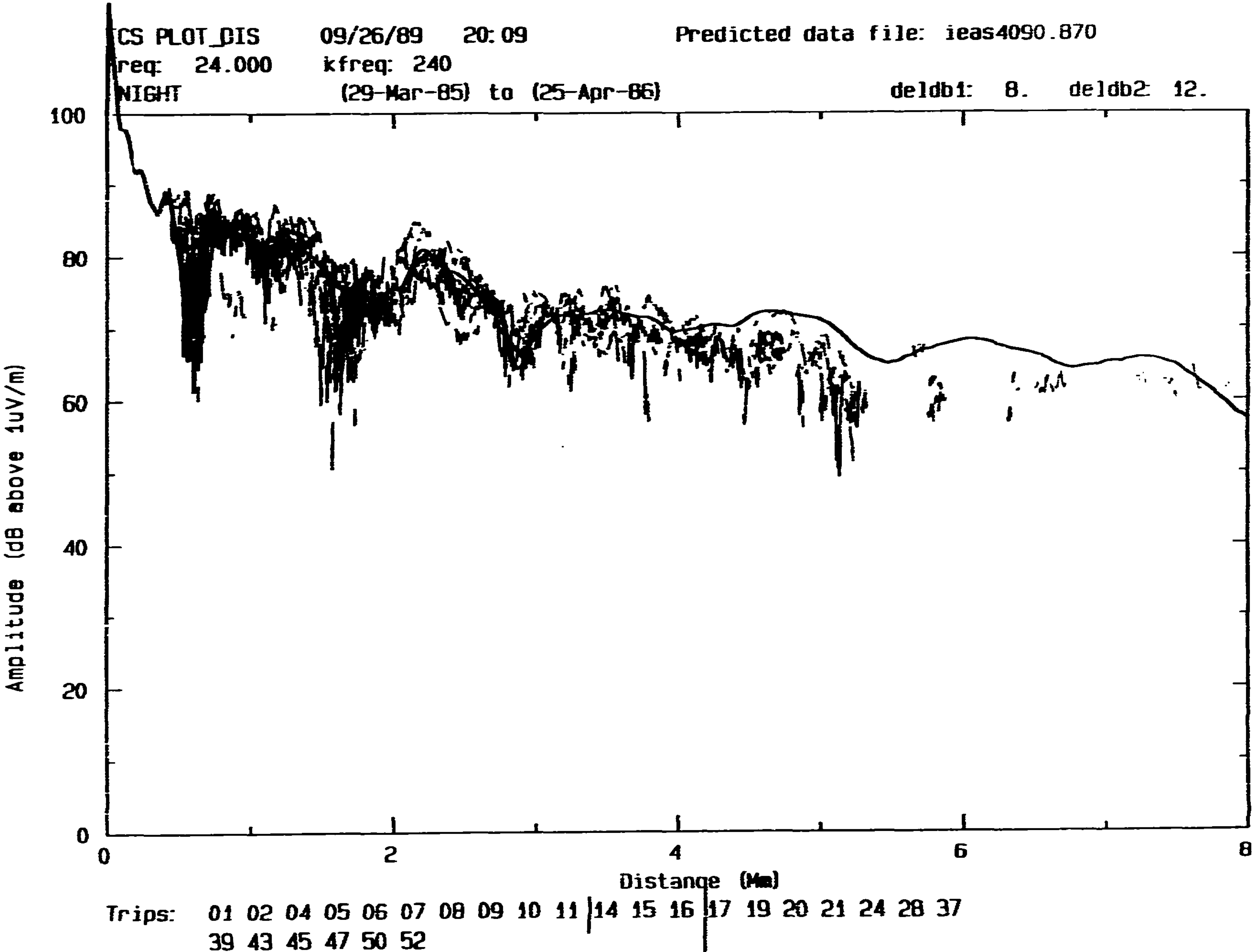


Figure 28. LWPC prediction for $\beta=0.54$, $h'=87$, PCAP=70-74, with recorded data for Cutler at 1000 kW, 24.0 kHz.

II-6.5 EXCURSIONS, ANNAPOLIS, 21.4 kHz, WITH PCAP = 80-84

The graphs of figures 29-33 repeat the profile selections of section II-6.3, except for the elimination of the LWPC's polar-area adjustment of $\beta - h'$ by setting PCAP = 80-84. Comparison of the two sets of graphs shows the introduction of even more high-order modes, and the best-fit selection is still a difficult choice.

One trend is evident: For this selection of β, deletion of the PCAP adjustment permits a better match to measured data at a lower h'. This group of graphs favors the curve fit of $h' = 85$, whereas in the PCAP = 70-74 cases a higher h' is preferred.

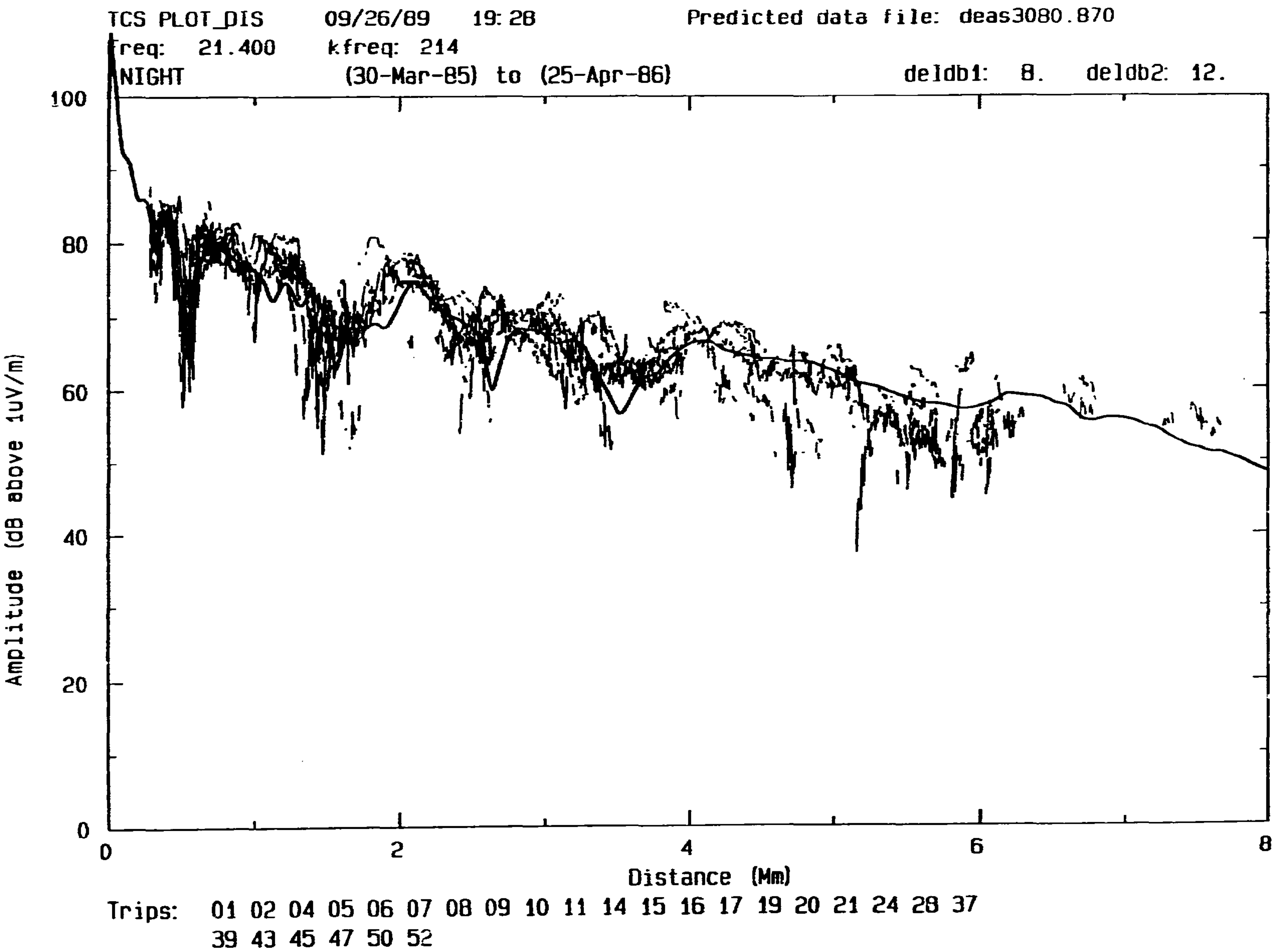


Figure 29. LWPC prediction for $\beta=0.41$, $h'=87$, (default), PCAP=80-84, with recorded data for Annapolis at 250 kW, 21.4 kHz.

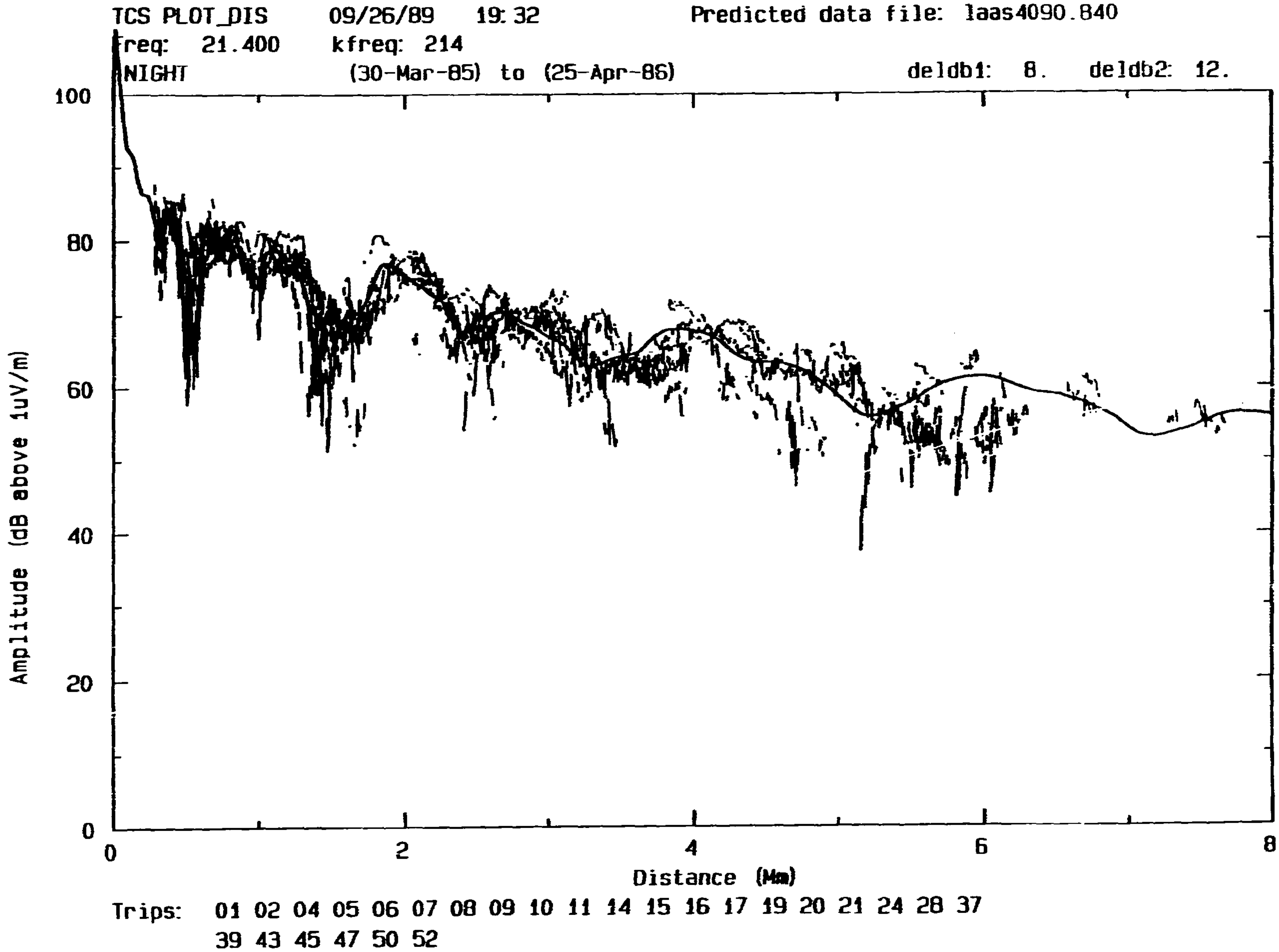


Figure 30. LWPC prediction for $\beta=0.51$, $h'=84$, PCAP=80-84, with recorded data for Annapolis at 250 kW, 21.4 kHz.

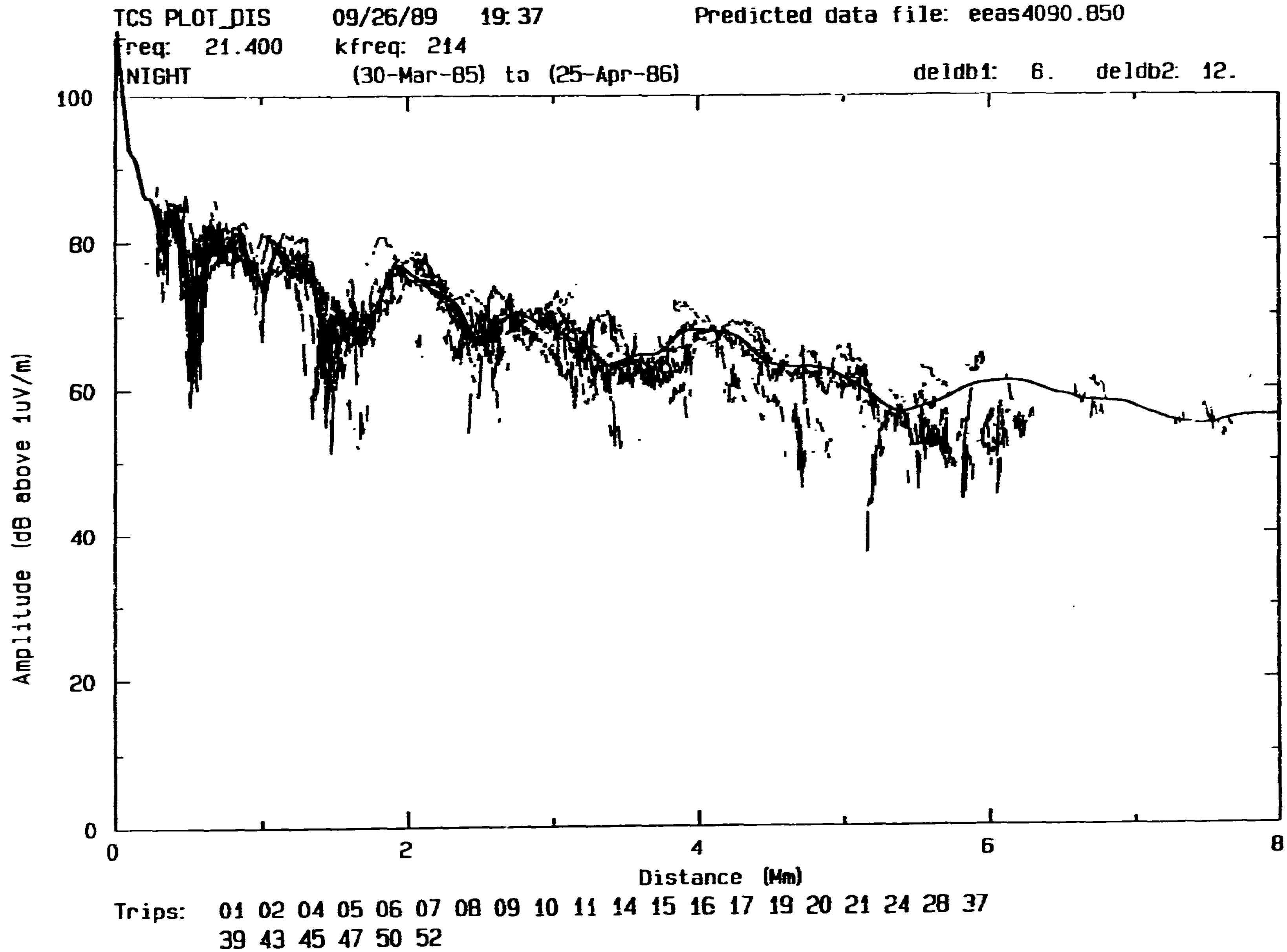


Figure 31. LWPC prediction for $\beta=0.51$, $h'=85$, PCAP=80-84, with recorded data for Annapolis at 250 kW, 21.4 kHz.

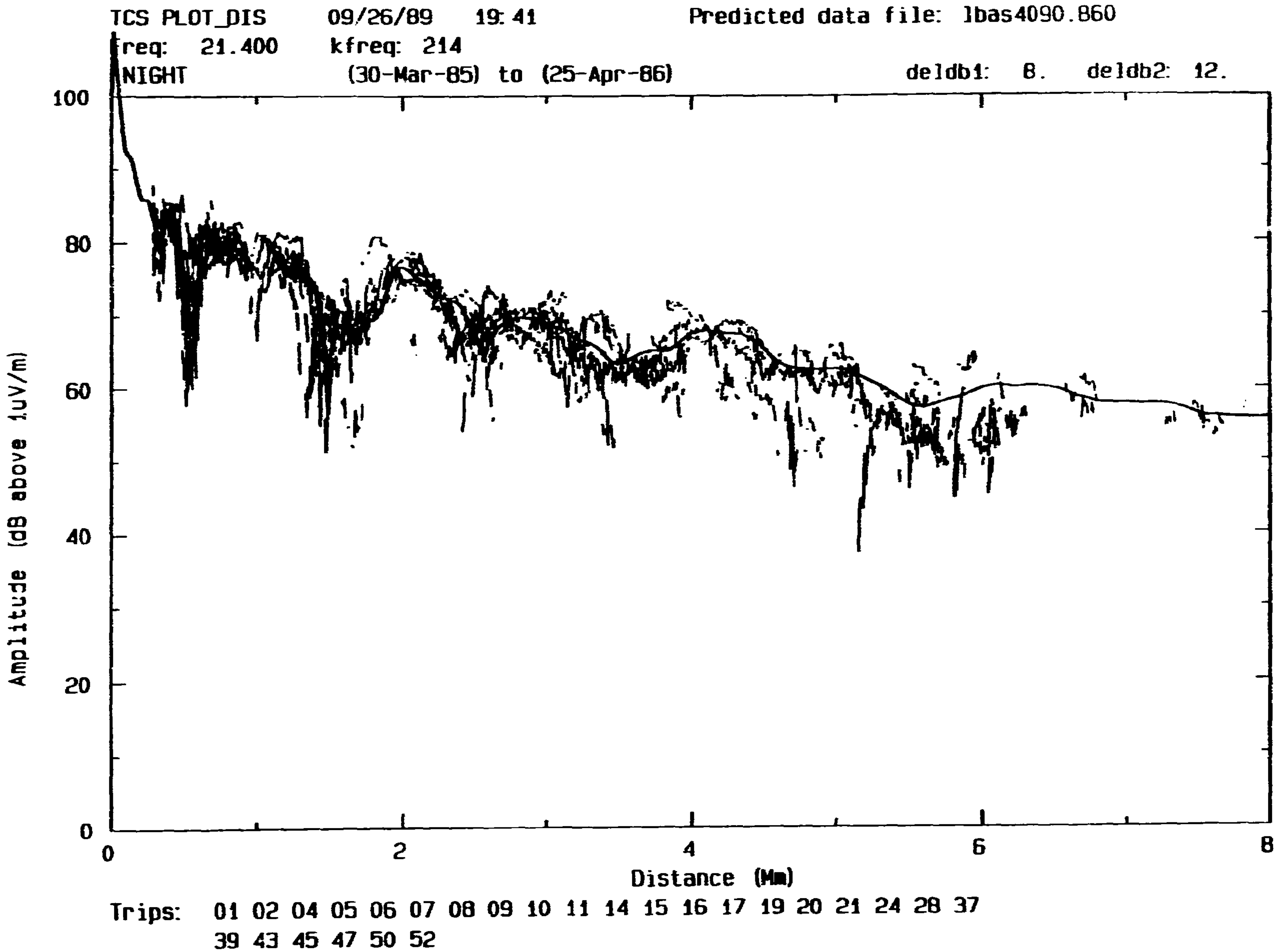


Figure 32. LWPC prediction for $\beta=0.51$, $h'=86$, PCAP=80-84, with recorded data for Annapolis at 250 kW, 21.4 kHz.

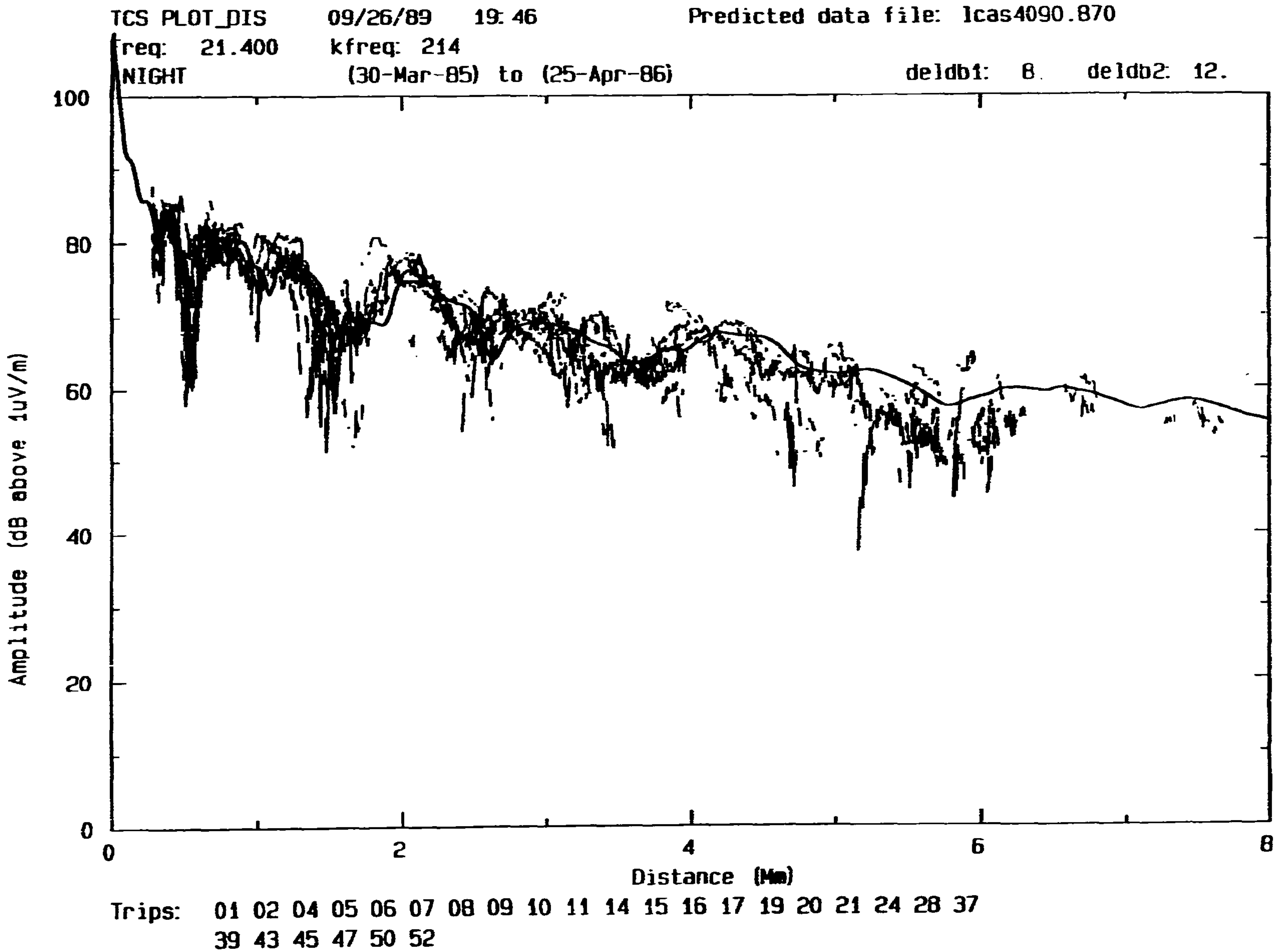


Figure 33. LWPC prediction for $\beta=0.51$, $h'=87$, PCAP=80-84, with recorded data for Annapolis at 250 kW, 21.4 kHz.

II-6.6 EXCURSIONS, CUTLER, 24.0 kHz, WITH PCAP = 80-84

Similar tradeoffs were noted in the 24.0-kHz cases of figures 34-38. The selection of a higher β range and the trend to lower h$'$ values resulted in better curve fits than in the default PCAP graphs.

No final conclusions could be reached about the PCAP adjustment in these limited tests; data fit seemed to suggest a tradeoff of PCAP range vs. h$'$. NOSC has suggested that more extensive tests of PCAP settings, taken over a much wider $\beta-$h$'$ range, should be conducted, and have recommended at least three ranges for the PCAP transition analysis: 80-84, 70-74 and 66-70.

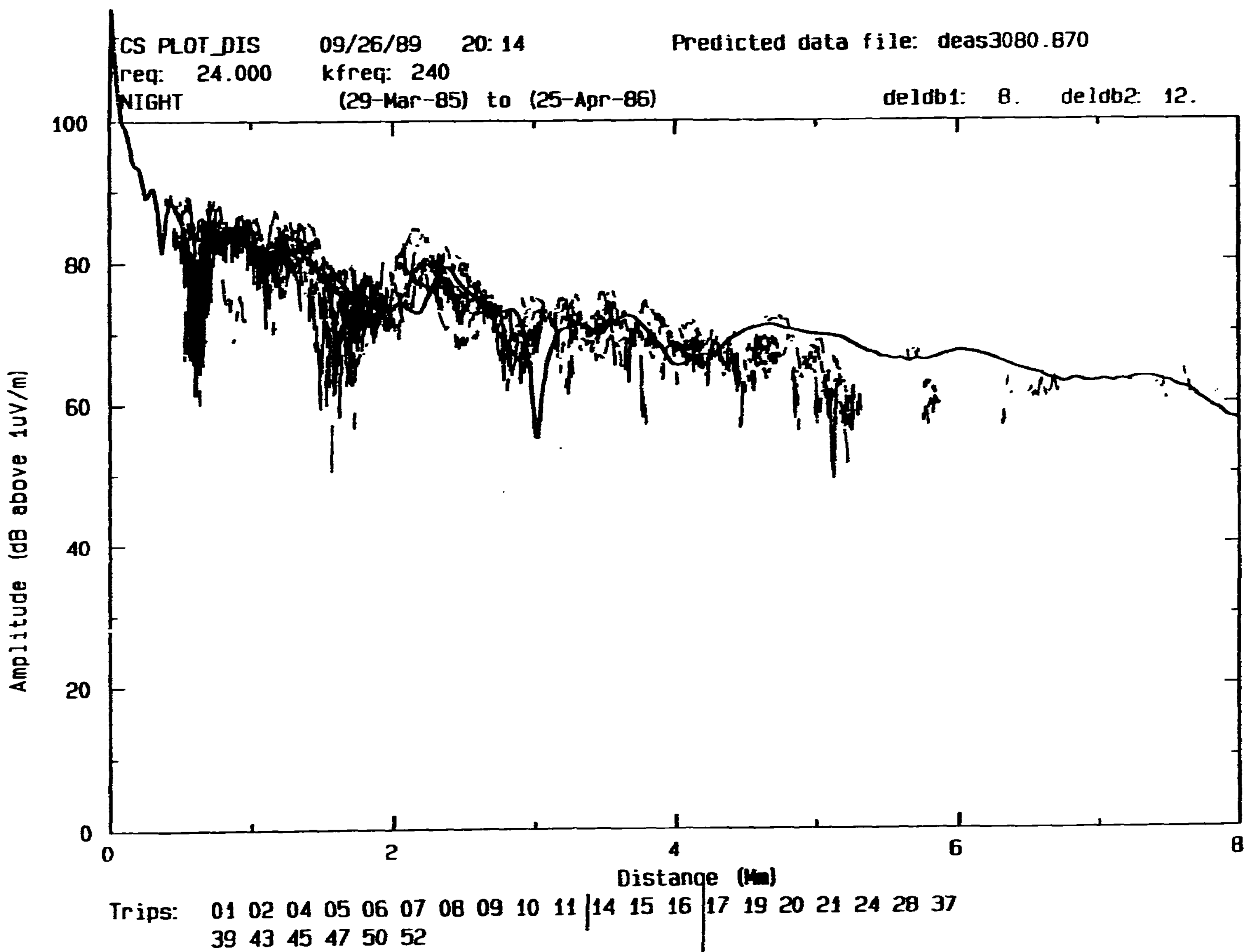


Figure 34. LWPC prediction for $\beta=0.44$, $h'=87$ (default), PCAP=80-84, with recorded data for Cutler at 1000 kW, 24.0 kHz.

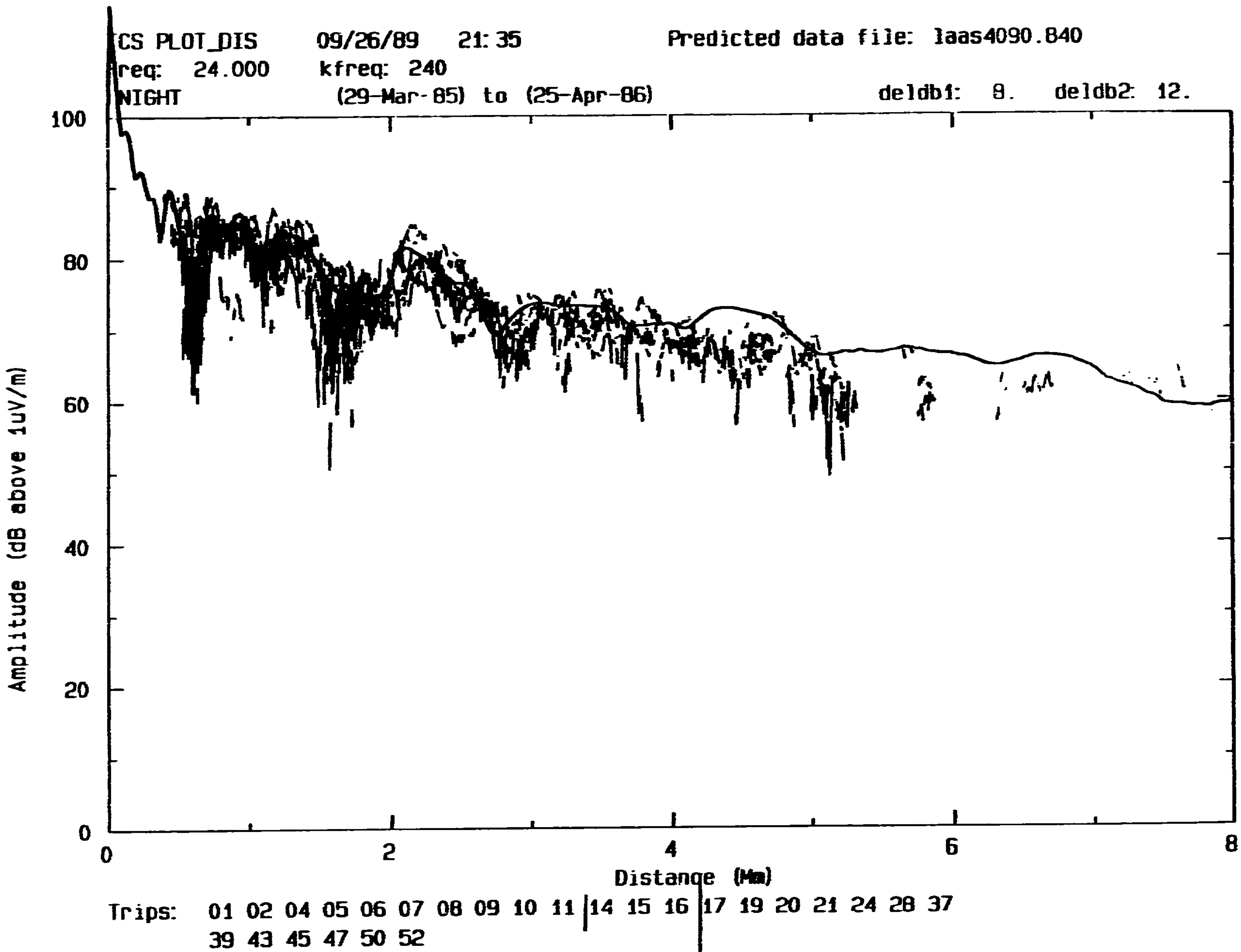


Figure 35. LWPC prediction for $\beta=0.54$, h' $=84$, PCAP$=80$-84, with recorded data for Cutler at 1000 kW, 24.0 kHz.

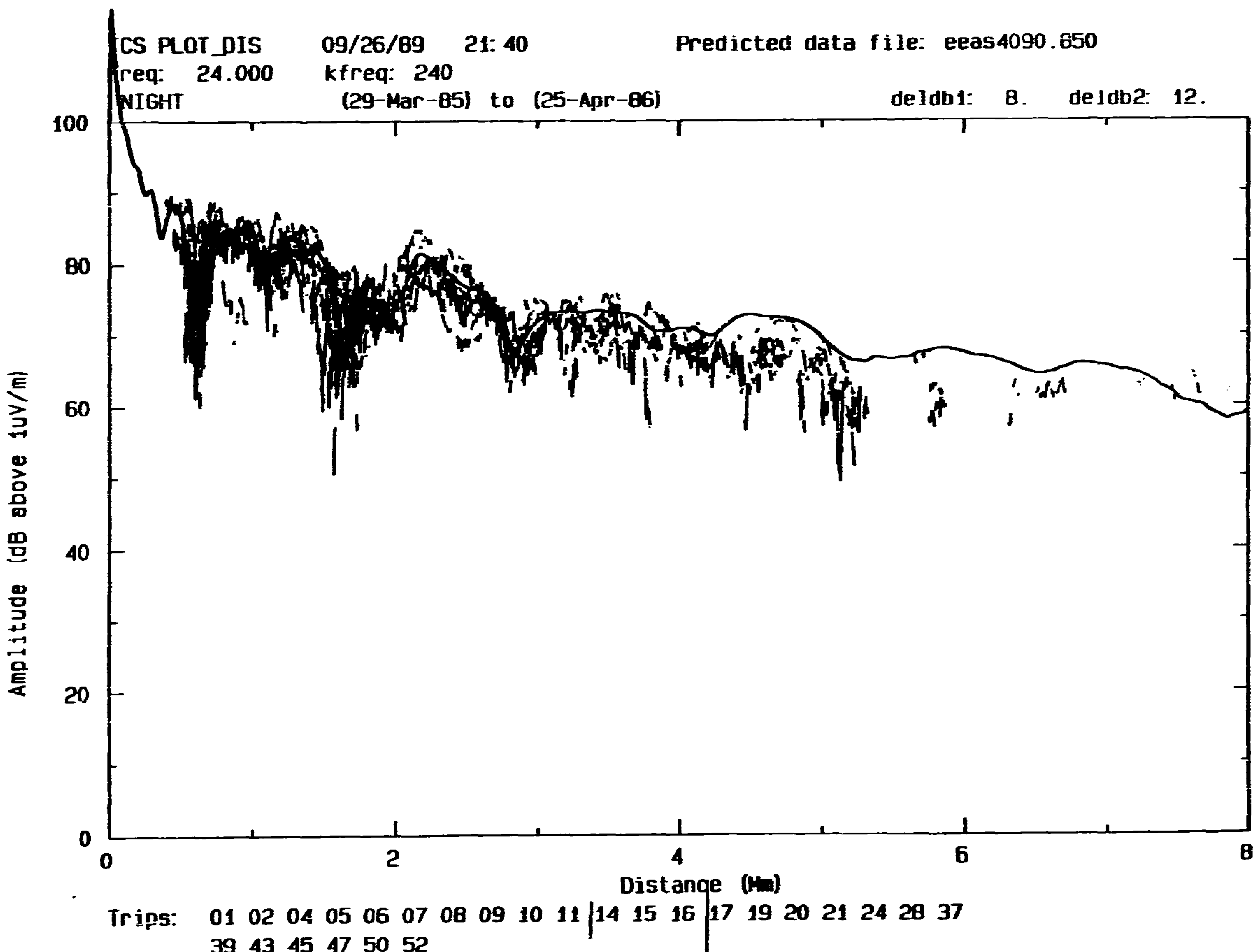


Figure 36. LWPC prediction for $\beta=0.54$, $h'=85$, PCAP=80-84, with recorded data for Cutler at 1000 kW, 24.0 kHz.

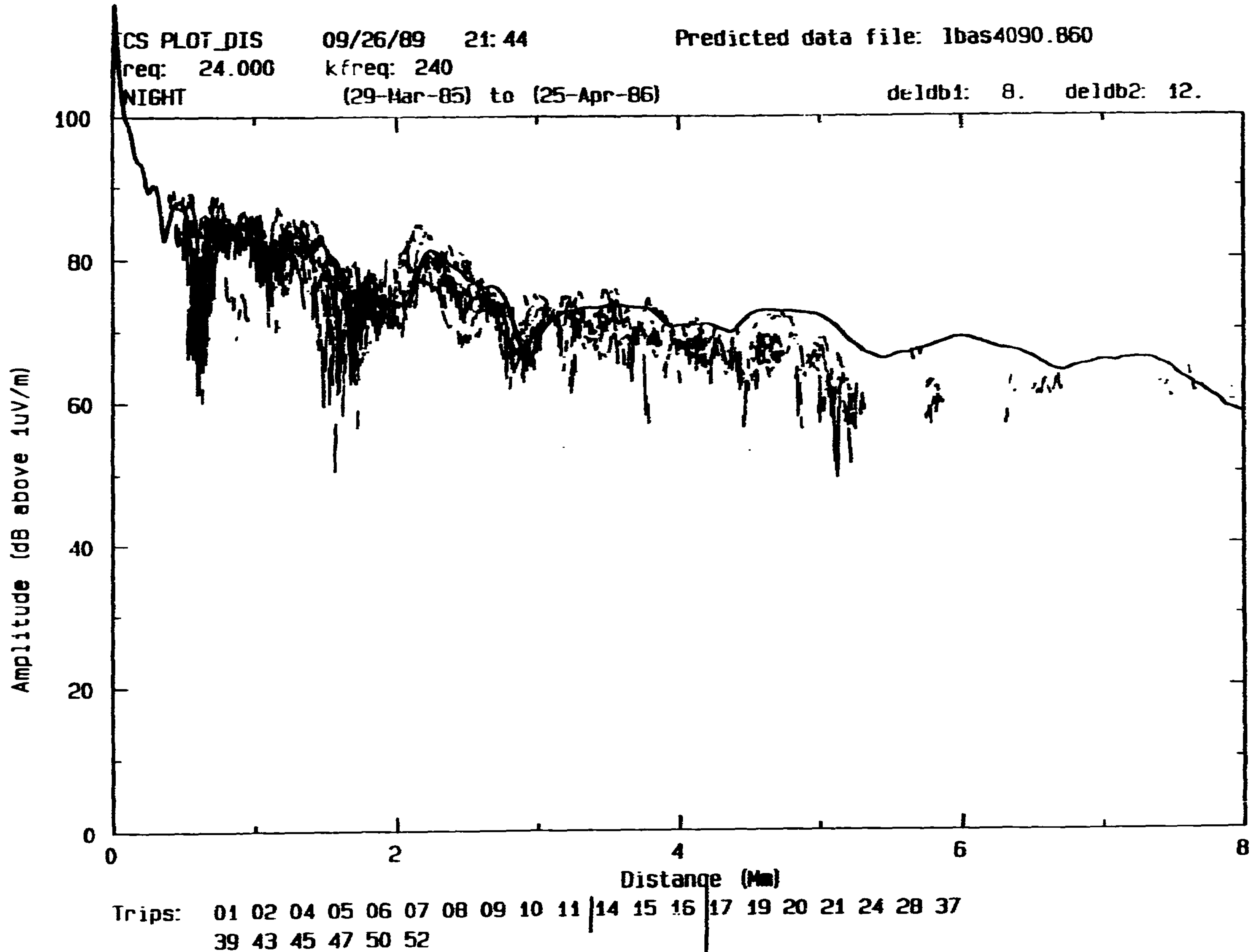


Figure 37. LWPC prediction for $\beta=0.54$, $h'=86$, PCAP=80-84, with recorded data for Cutler at 1000 kW, 24.0 kHz.

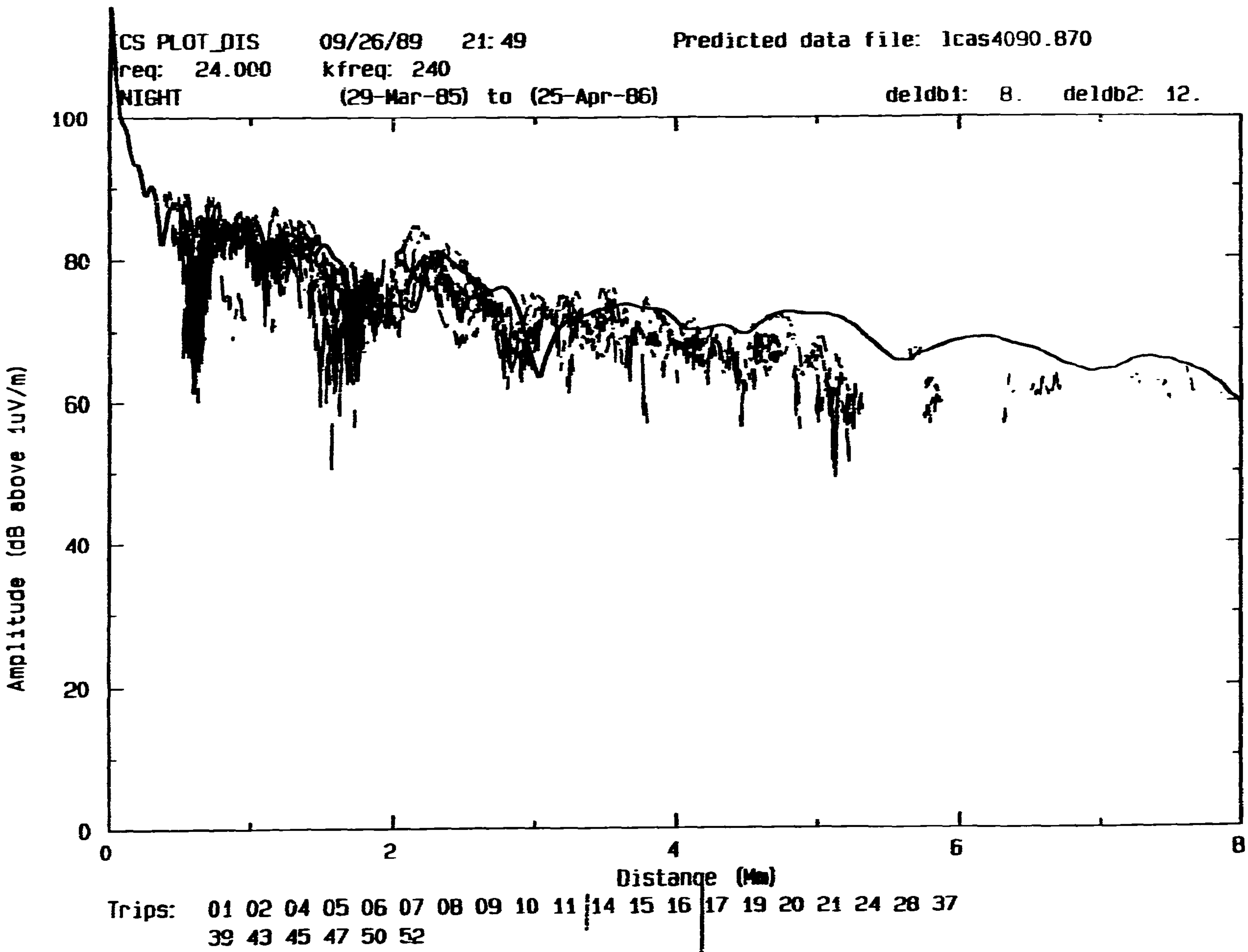


Figure 38. LWPC prediction for $\beta=0.54$, $h'=87$, PCAP=80-84, with recorded data for Cutler at 1000 kW, 24.0 kHz.

SECTION II-7

STATISTICAL ANALYSES

II-7.1 RUGBY, 16.0 kHz

While the graphs of the previous section are useful for quick comparisons of the total data set by the human eye, the NOSC program TRIPSTAT provides a better technique for quantitative evaluation. In section II-7, statistical graphs from TRIPSTAT runs are presented for each case of the earlier sequence.

The statistical charts of recorded-minus-predicted signal strength in dB at 16.0 kHz are given in figures 39-43. Each chart presents separate histograms at 125-km intervals along the path, evaluating the distribution of data points recorded within a range of ±60 km from each 125-km interval. The total number of recorded points within each ±60-km range are graphed in the lower chart of each sheet.

Each histogram is divided into 1-dB bins, the height of which varies in proportion to the number of data points in each 1-dB interval. In addition, mean (diamond) and 90% exceedance level (x) values are displayed below each histogram. An overall measure of goodness is the degree with which the histogram and its mean are centered on the 0-dB axis. A 0-dB mean with all data points centered on the axis would represent a perfect match between recorded and predicted signal levels at that distance.

The statistical graph for the LWPC default profile at 16 kHz is shown in figure 39, where the cyclic nature of the recorded-minus-predicted data reflects the mismatch between the fading cycles displayed in figure 9, page 35. The distribution of means is improved somewhat by the series of charts in figures 40-43, but these quantitative analyses confirm that the nighttime ionosphere is quite variable with respect to the much closer fits of daytime data in the earlier Callaghan report. This quantitative evaluation nevertheless permits a better evaluation of one profile against the other, as is seen by simply scanning the distribution of mean values.

The statistical graphs were the main means for optimizing the selection of best-fit profiles in this task, considering the limited number of profiles examined. A method for automating this selection over a greater number of choices is discussed in section II-7.7.

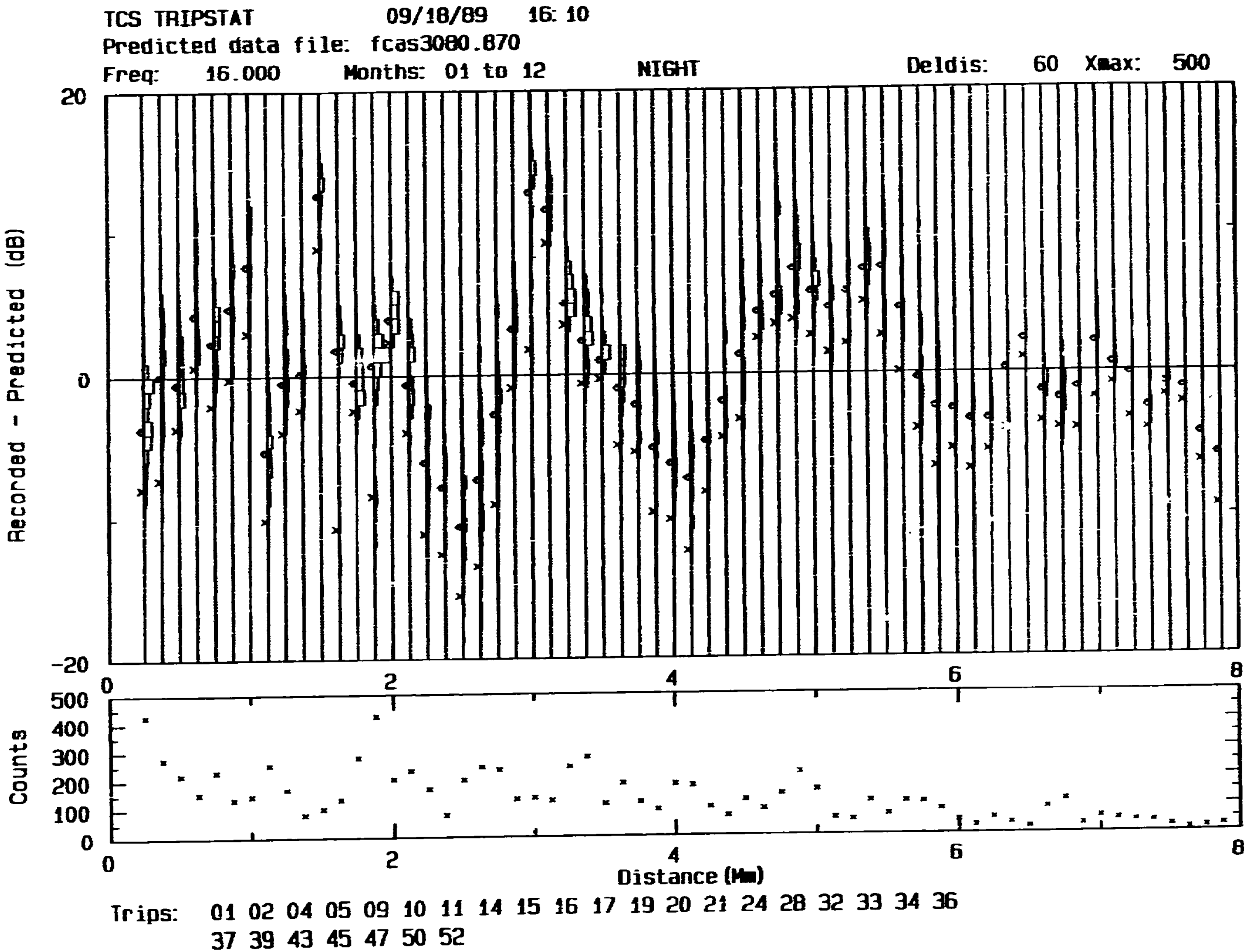


Figure 39. Recorded − predicted data, Rugby at 65 kW, 16.0 kHz, with default LWPC prediction for $\beta=0.36$, $h'=87$, PCAP=70-74.

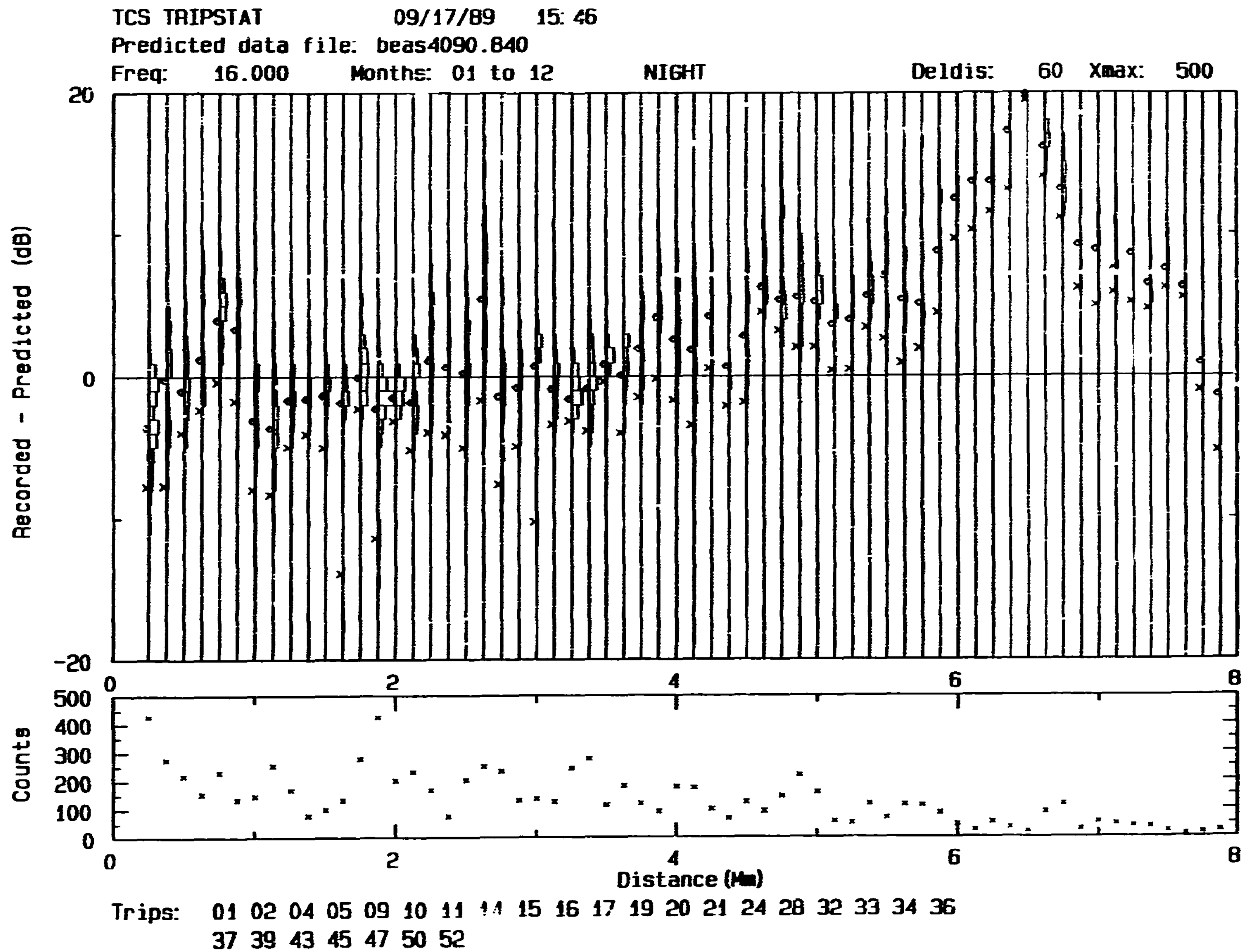


Figure 40. Recorded – predicted data, Rugby at 65 kW, 16.0 kHz, with LWPC prediction for $\beta=0.46$, $h'=84$, PCAP=70-74.

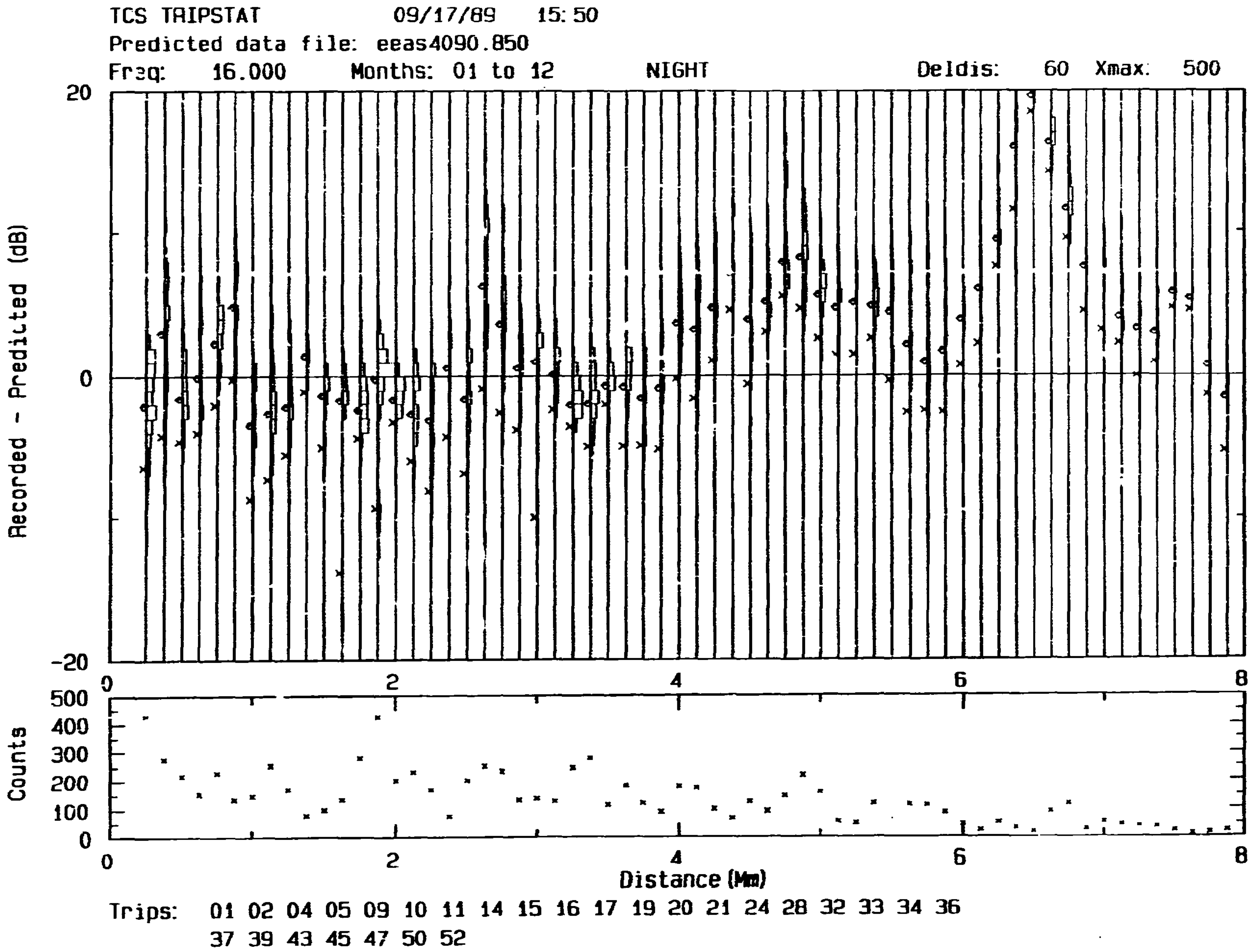


Figure 41. Recorded – predicted data, Rugby at 65 kW, 16.0 kHz, with LWPC prediction for β=0.46, h′=85, PCAP=70-74.

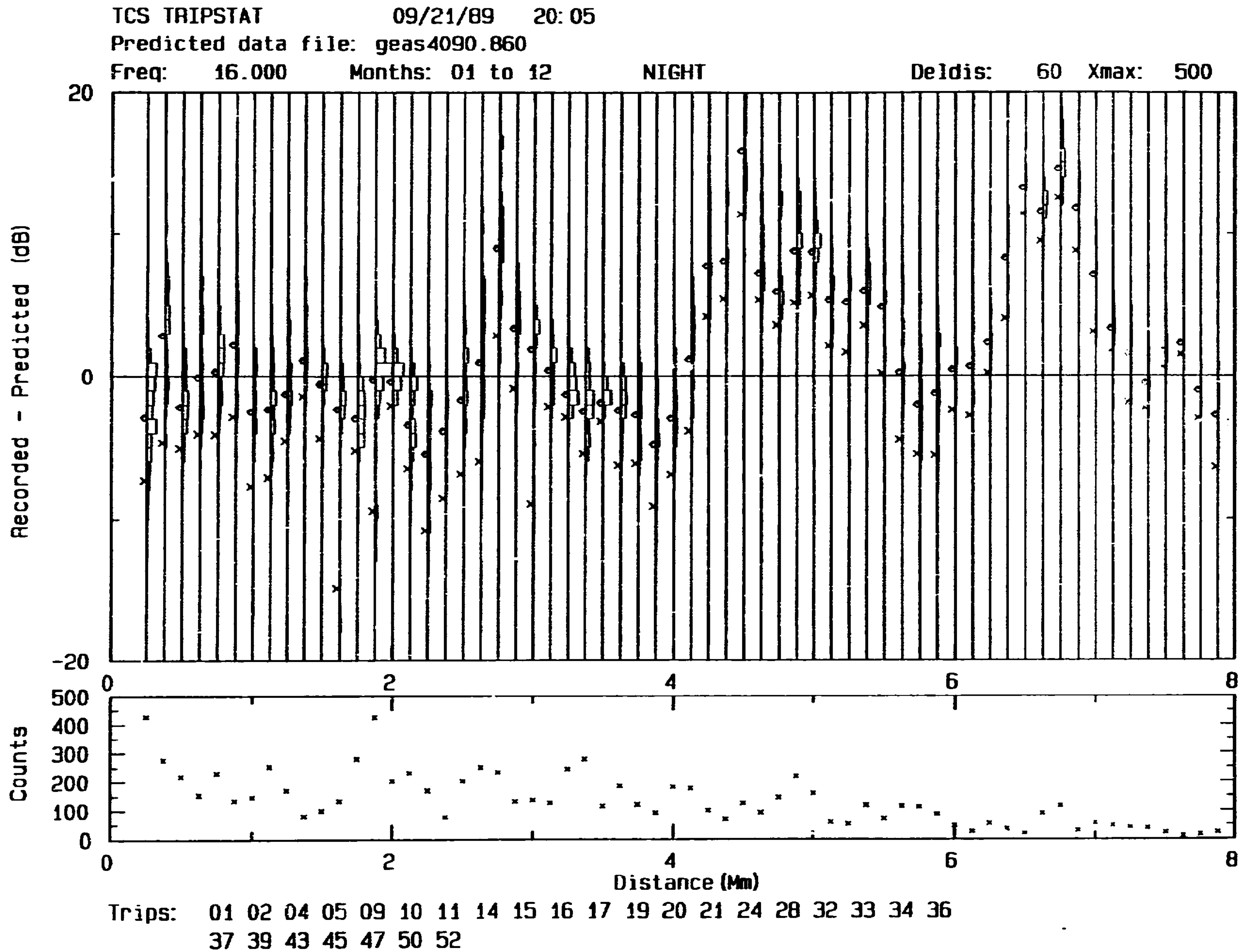


Figure 42. Recorded – predicted data, Rugby at 65 kW, 16.0 kHz, with LWPC prediction for $\beta = 0.46$, $h' = 86$, PCAP = 70-74.

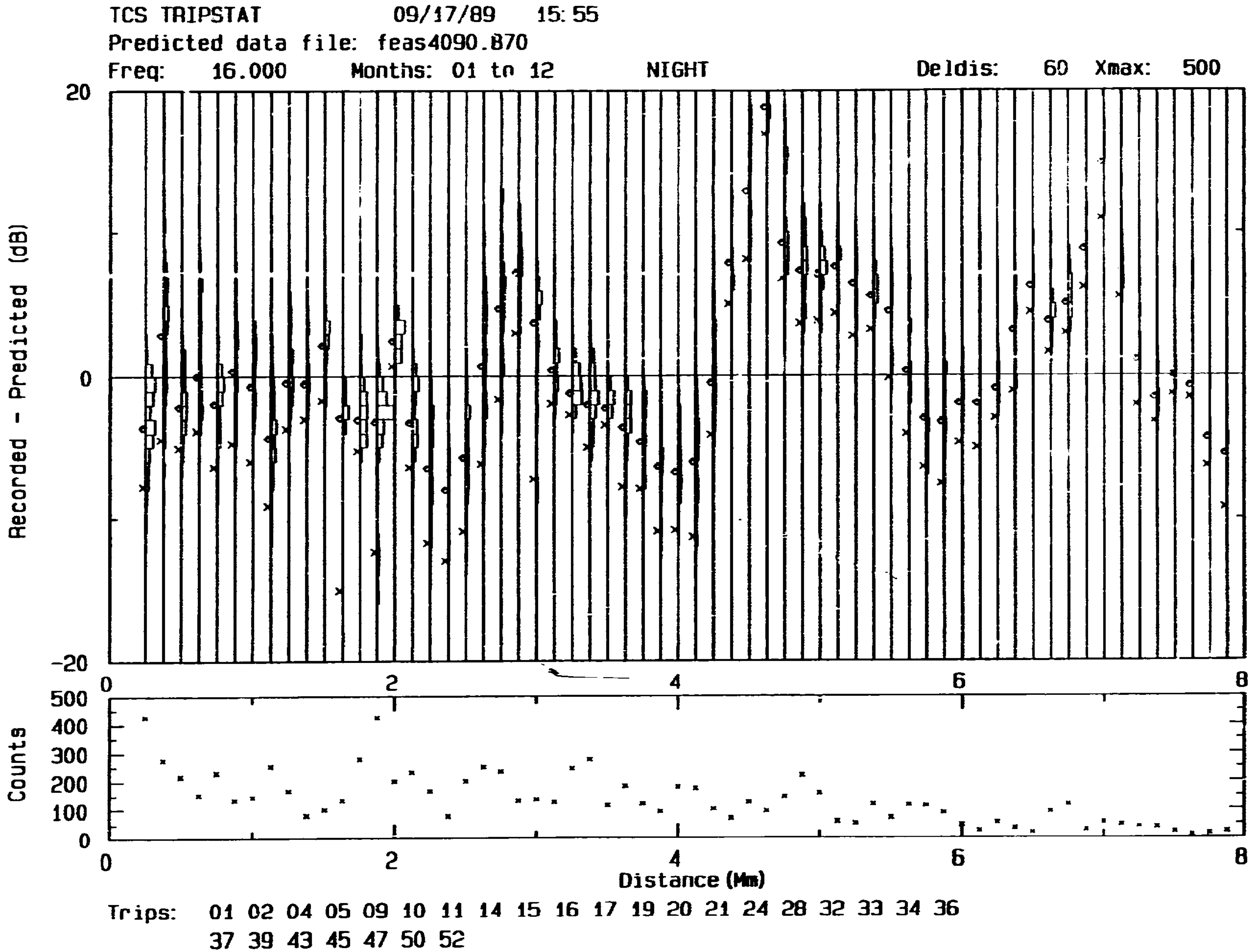


Figure 43. Recorded – predicted data, Rugby at 65 kW, 16.0 kHz, with LWPC prediction for $\beta=0.46$, $h'=87$, PCAP=70-74.

II-7.2 ANTHORNE, 19.0 kHz

The statistical comparison between the LWPC default and the optimized $\beta-h'$ values is more favorable in the 19.0-kHz examples of figures 44-48. The distribution of means in the default case is scattered over a wide range, while the means of the 85-km example of figure 46 are relatively well behaved, with most falling within a ±4-dB range out to 4.5-Mm distance.

The distribution of 90% exceedance values is seen as a less favorable indicator of fit than is that of the means in figure 46, where the existence of spurious data points, particularly around fades as is typical of the nighttime ionosphere, produces large values for the 90% exceedance points.

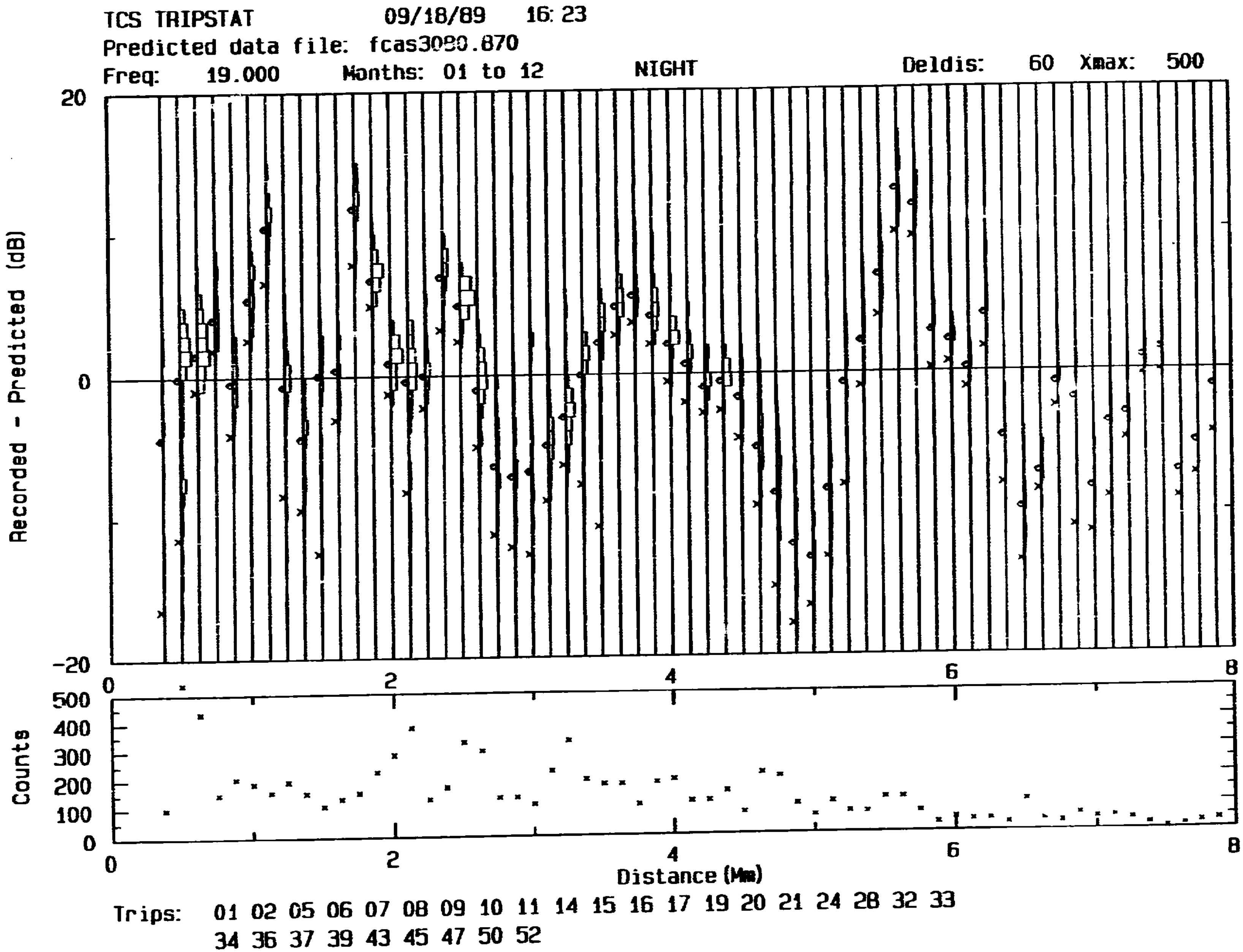


Figure 44. Recorded – predicted data, Anthorne at 80 kW, 19.0 kHz, with default LWPC prediction for $\beta=0.39$, $h'=87$, PCAP=70-74.

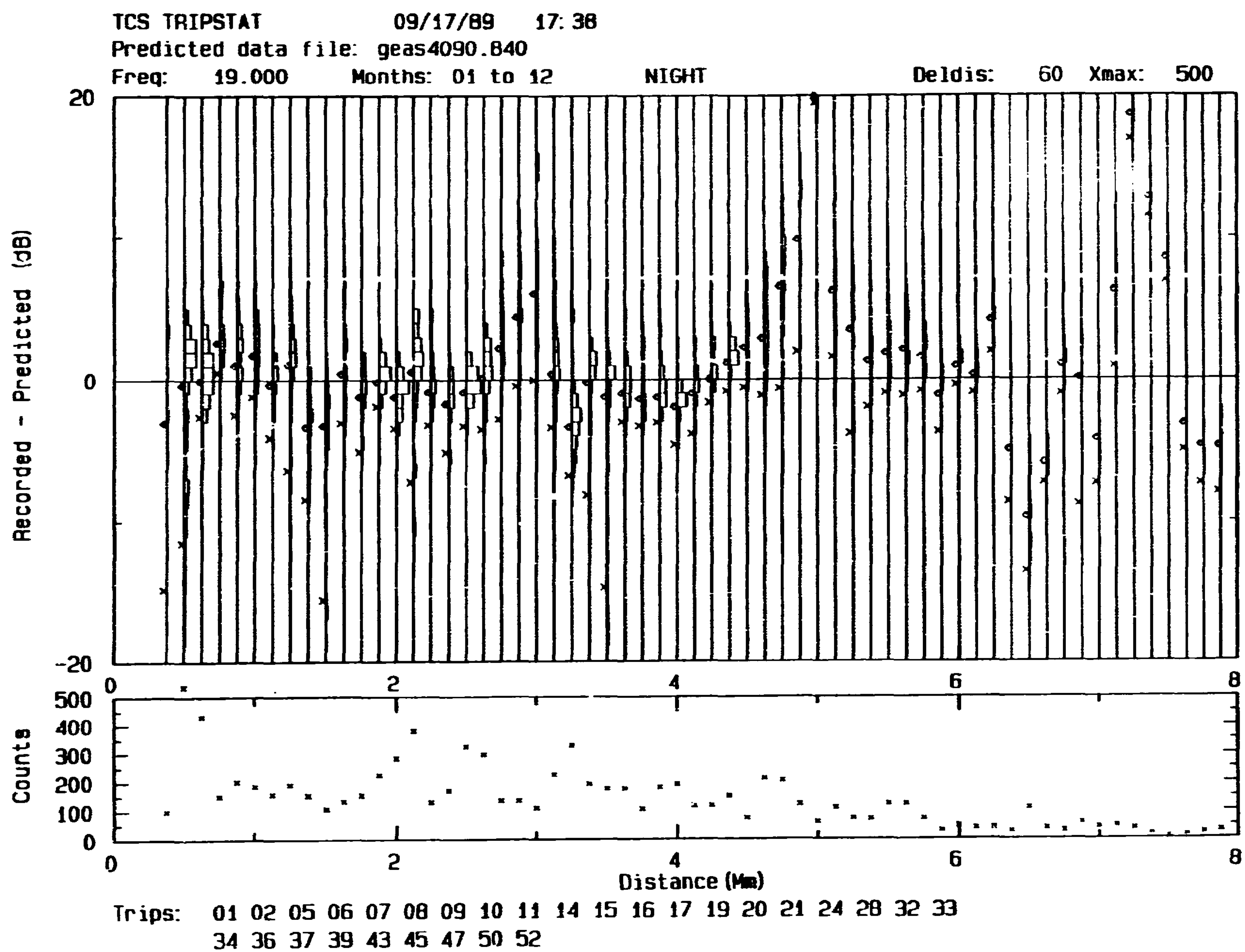


Figure 45. Recorded – predicted data, Anthorne at 80 kW, 19.0 kHz, with LWPC prediction for $\beta=0.49$, $h'=84$, PCAP=70-74.

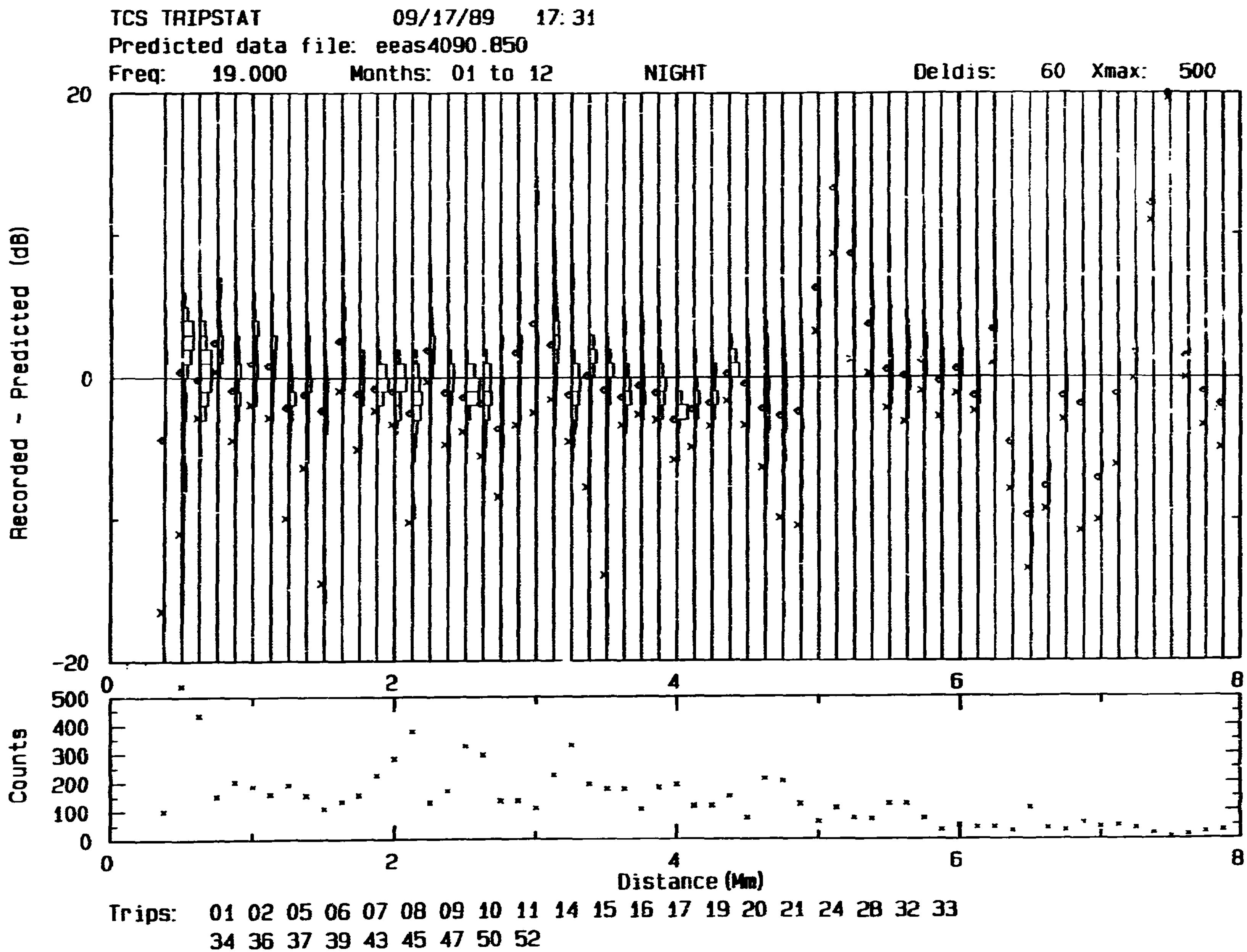


Figure 46. Recorded – predicted data, Anthorne at 80 kW, 19.0 kHz, with LWPC prediction for $\beta=0.49$, $h'=85$, PCAP=70-74.

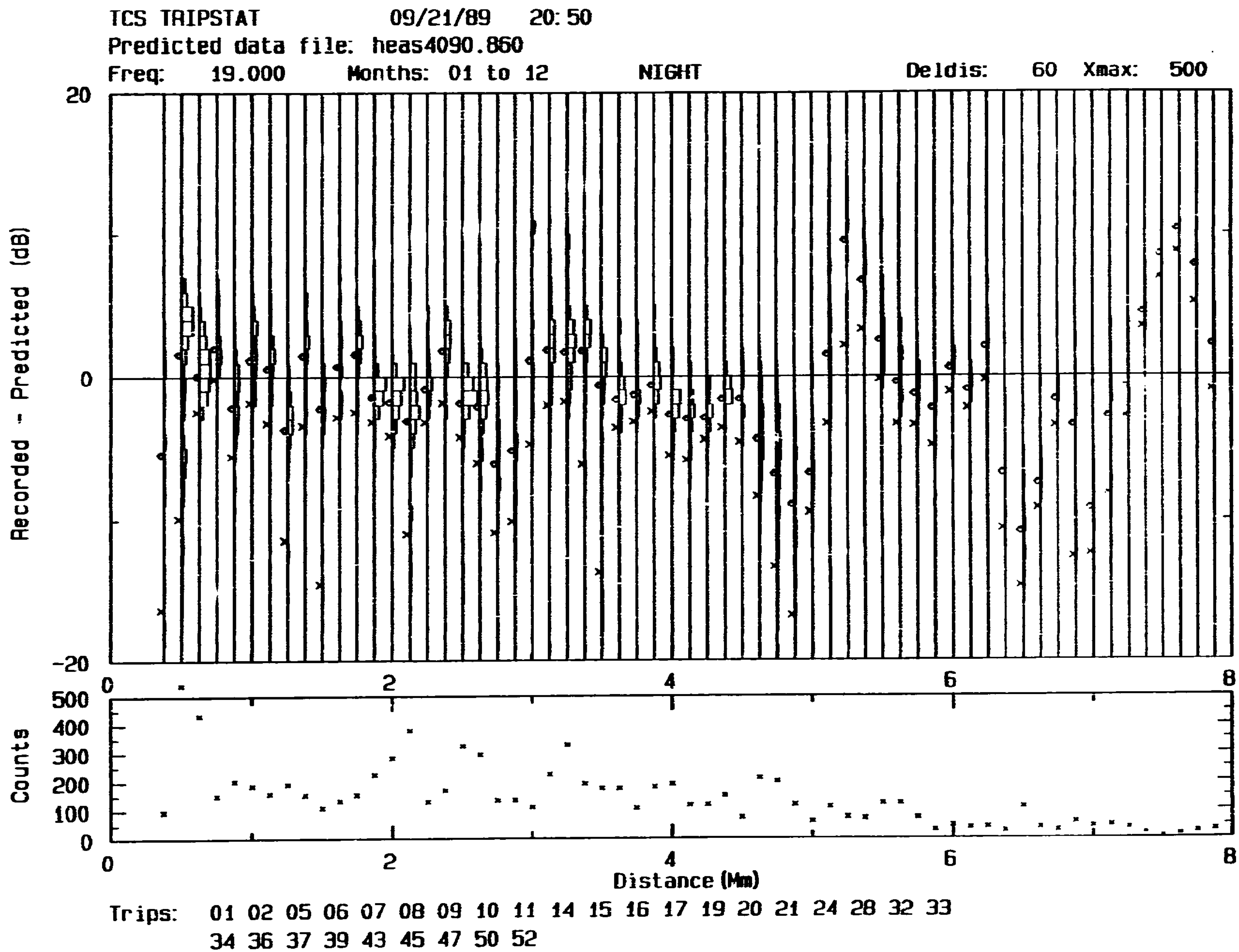


Figure 47. Recorded – predicted data, Anthorne at 80 kW, 19.0 kHz, with LWPC prediction for $\beta=0.49$, $h'=86$, PCAP=70-74.

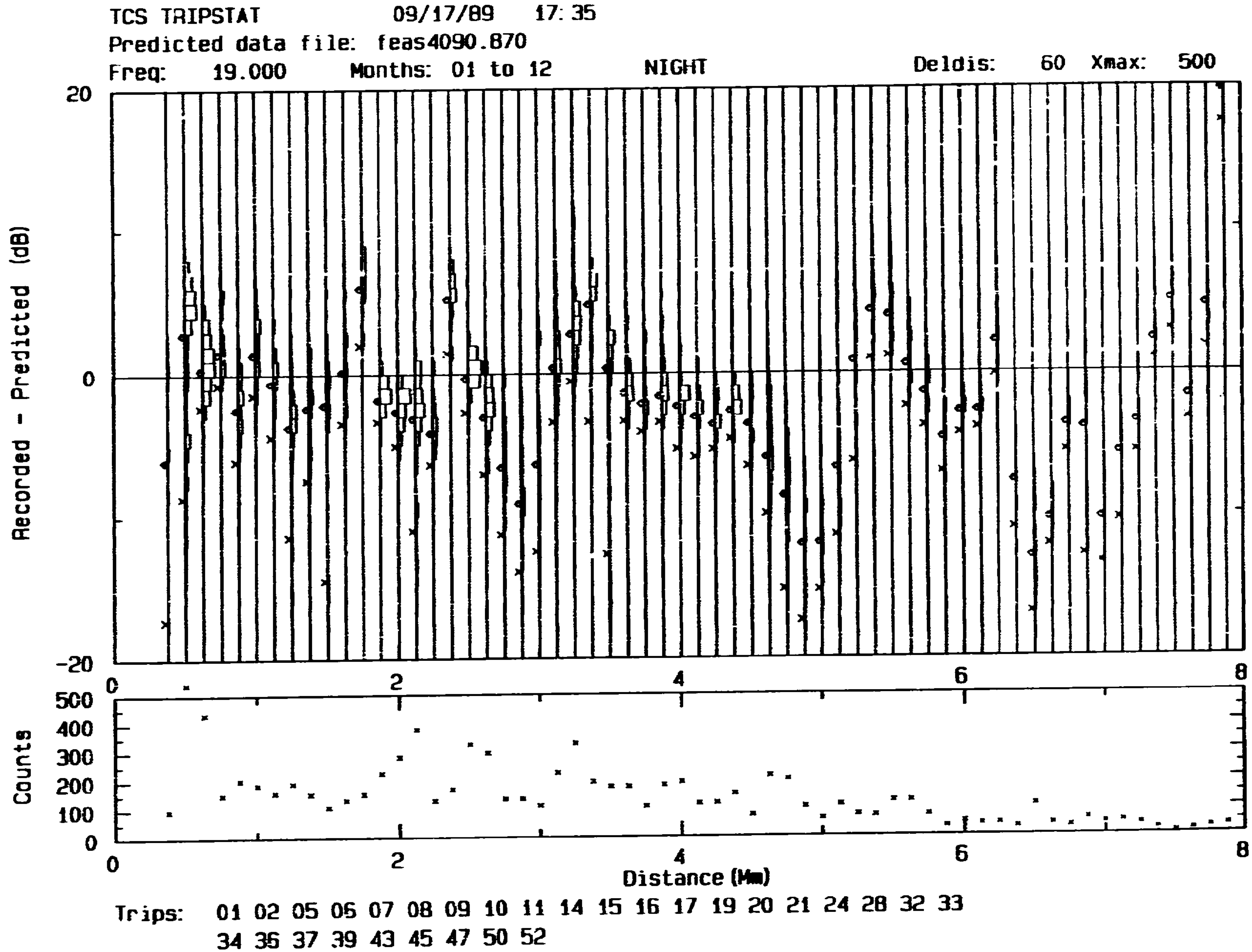


Figure 48. Recorded – predicted data, Anthorne at 80 kW, 19.0 kHz, with LWPC prediction for $\beta=0.49$, $h'=87$, PCAP=70-74.

II-7.3 ANNAPOLIS, 21.4 kHz

The LWPC default profile provides a much better fit in the 21.4-kHz case, as is seen by the charts of figure 49. The charts of figures 50-53, for the $\beta = 0.40$-0.90 profile are worse than those of figure 49 at the shorter waveguide heights. The best fit for this profile sequence is found for $h' = 87$ km, in figure 53, where all but one mean value fall within a ±3-dB range, and this fit extends past the 5-Mm distance.

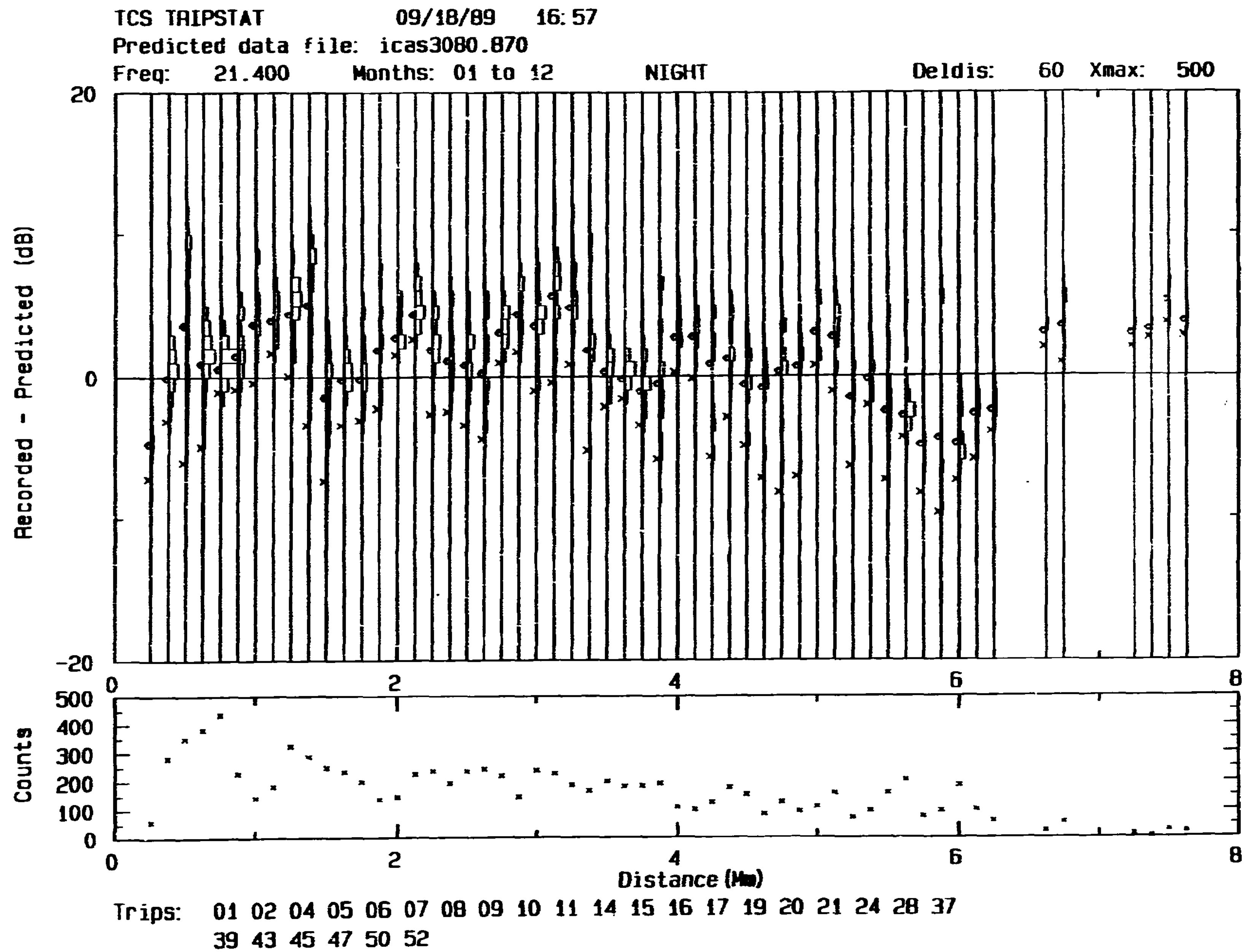


Figure 49. Recorded – predicted data, Annapolis at 250 kW, 21.4 kHz, with default LWPC prediction for $\beta=0.41$, $h'=87$, PCAP=70-74.

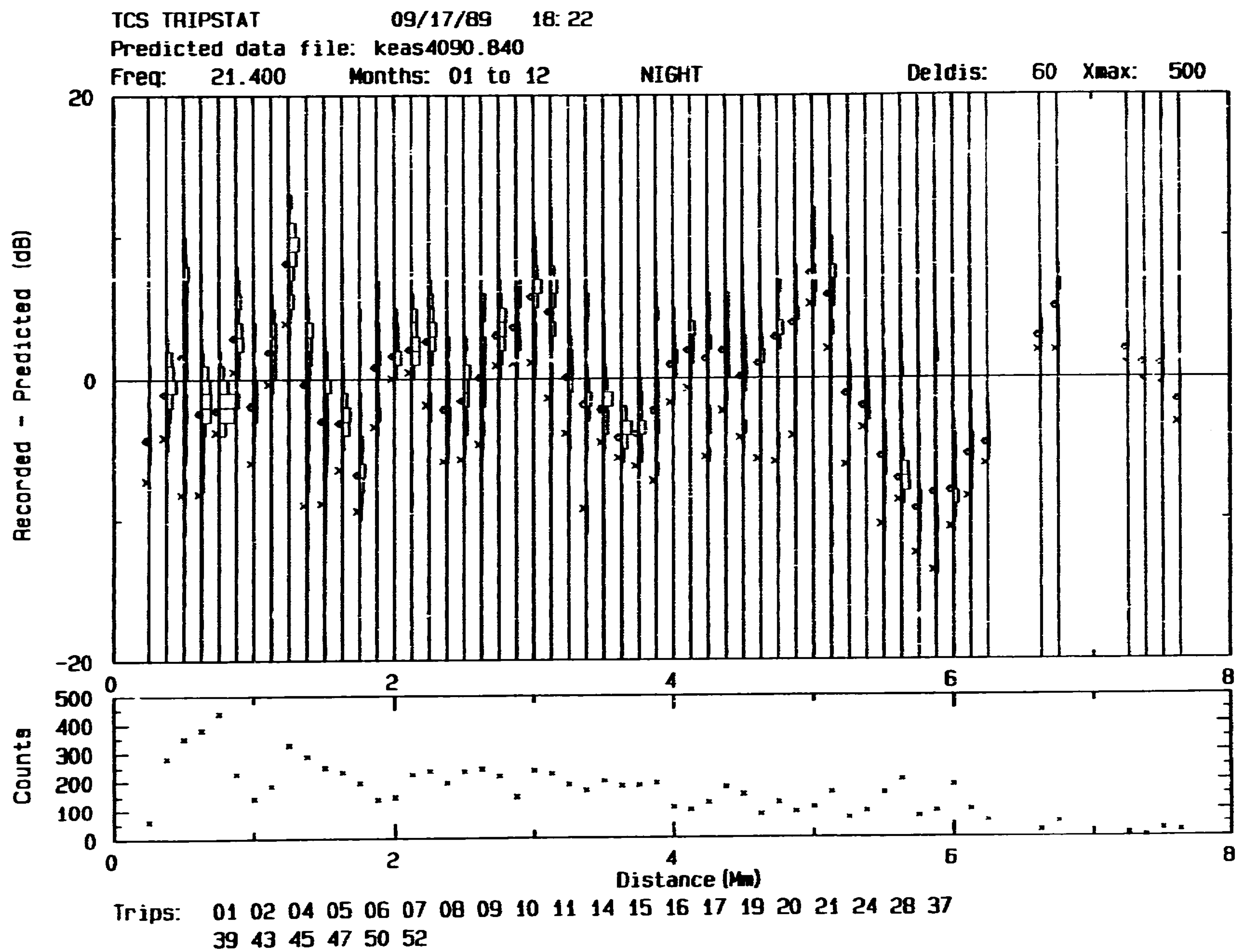


Figure 50. Recorded – predicted data, Annapolis at 250 kW, 21.4 kHz, with LWPC prediction for $\beta=0.51$, $h'=84$, PCAP=70-74.

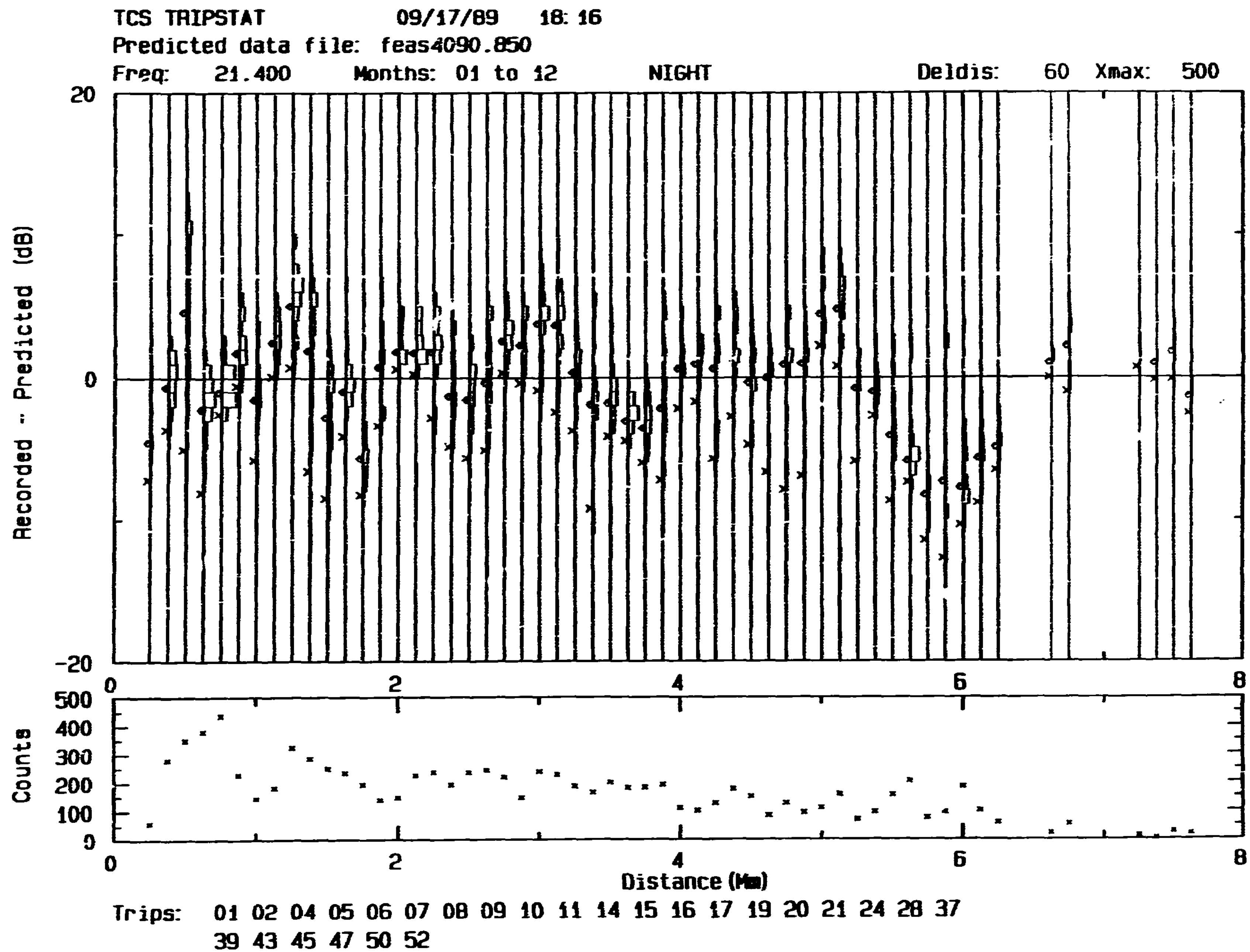


Figure 51. Recorded – predicted data, Annapolis at 250 kW, 21.4 kHz, with LWPC prediction for $\beta=0.51$, $h'=85$, PCAP=70-74.

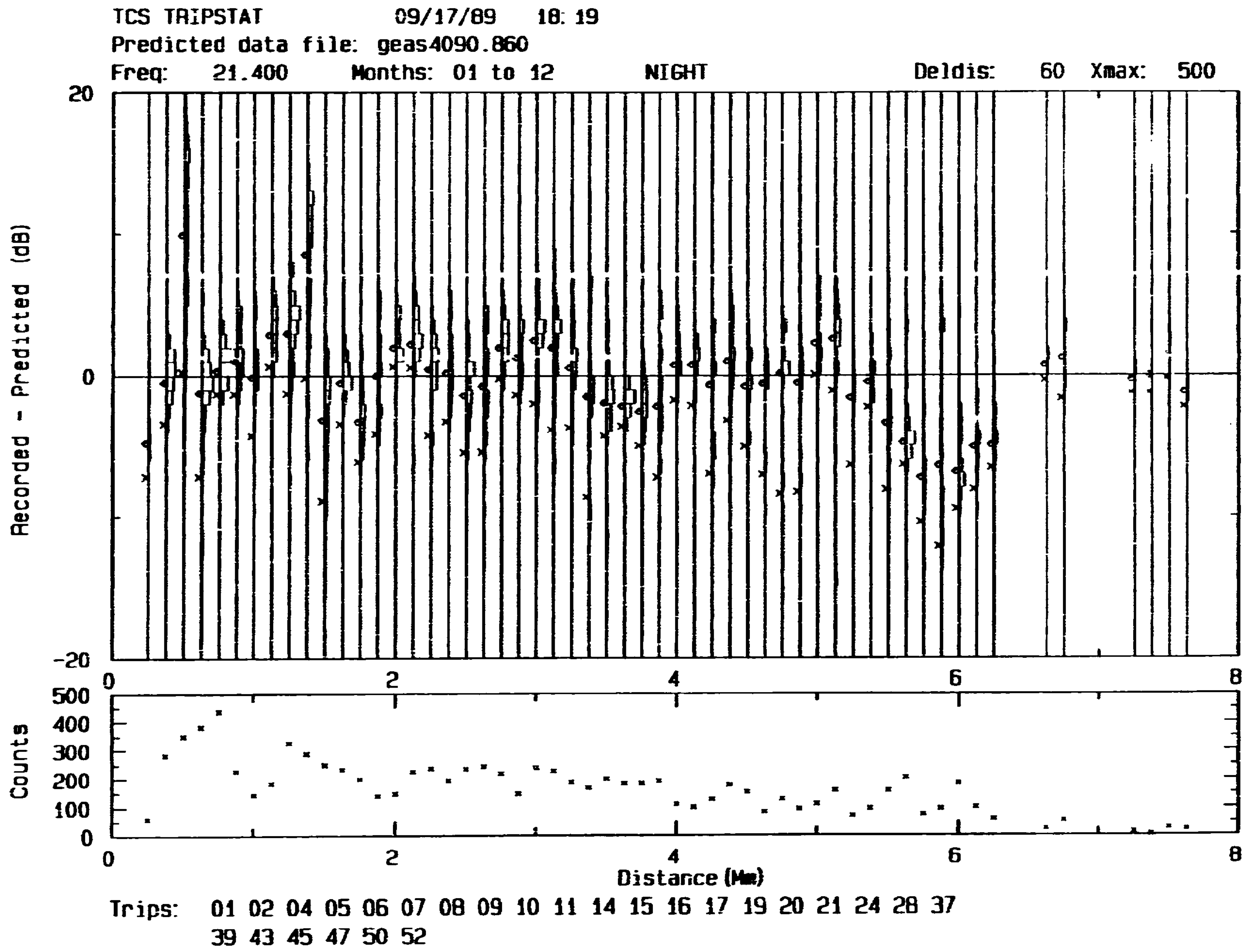


Figure 52. Recorded – predicted data, Annapolis at 250 kW, 21.4 kHz, with LWPC prediction for $\beta=0.51$, $h'=86$, PCAP=70-74.

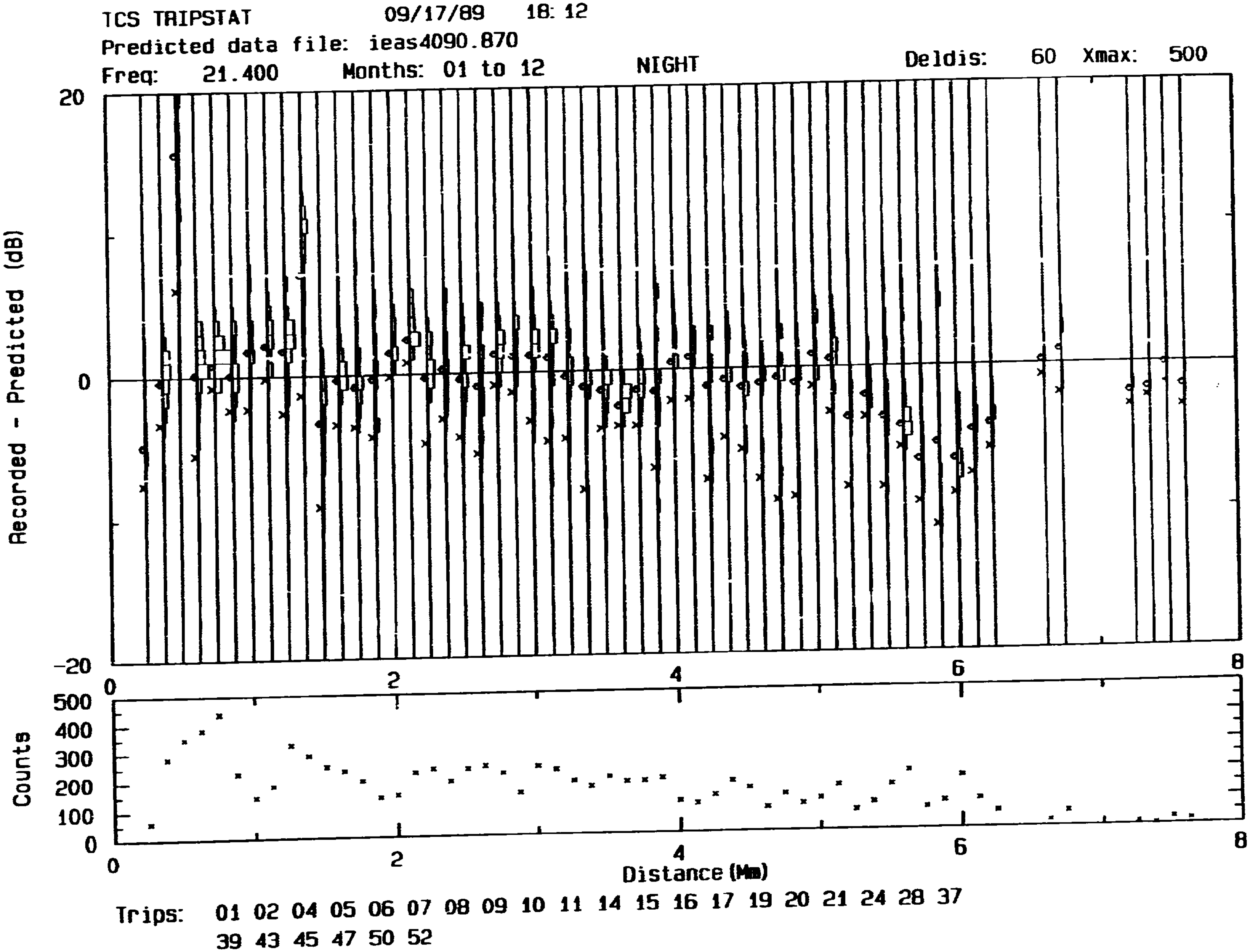


Figure 53. Recorded – predicted data, Annapolis at 250 kW, 21.4 kHz, with LWPC prediction for $\beta=0.51$, $h'=87$, PCAP = 70-74.

II-7.4 CUTLER, 24.0 kHz

The statistical evaluations for 24.0 kHz show that the $\beta - h' = 0.40$-0.90 profile offers an improvement over the LWPC default profile, as is shown in figures 54-58. The distribution of mean values is again best at $h' = 87$ km, but fewer points are within the ± 3-dB range.

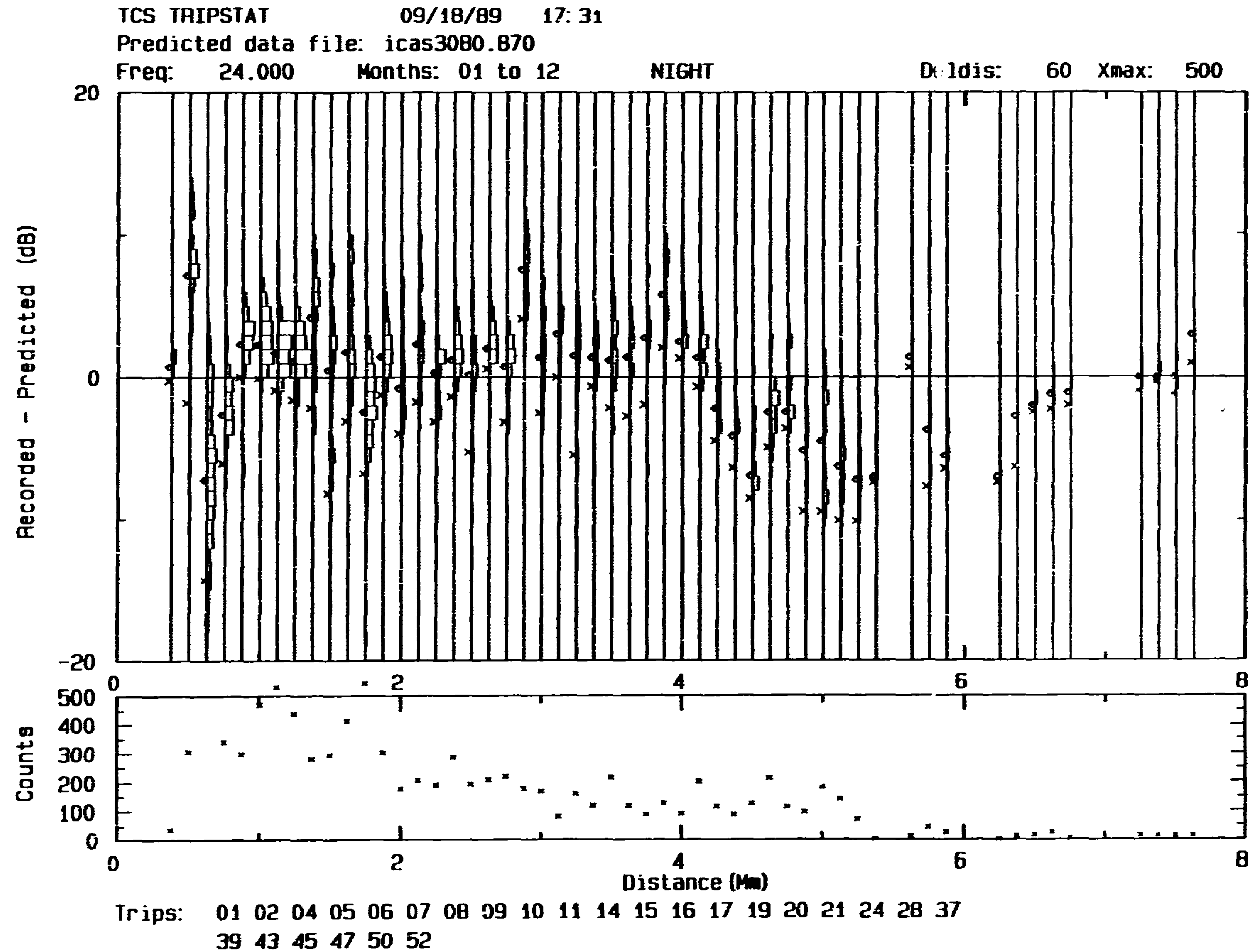


Figure 54. Recorded – predicted data, Cutler at 1000 kW, 24.0 kHz, with default LWPC prediction for $\beta=0.44$, $h'=87$, PCAP=70-74.

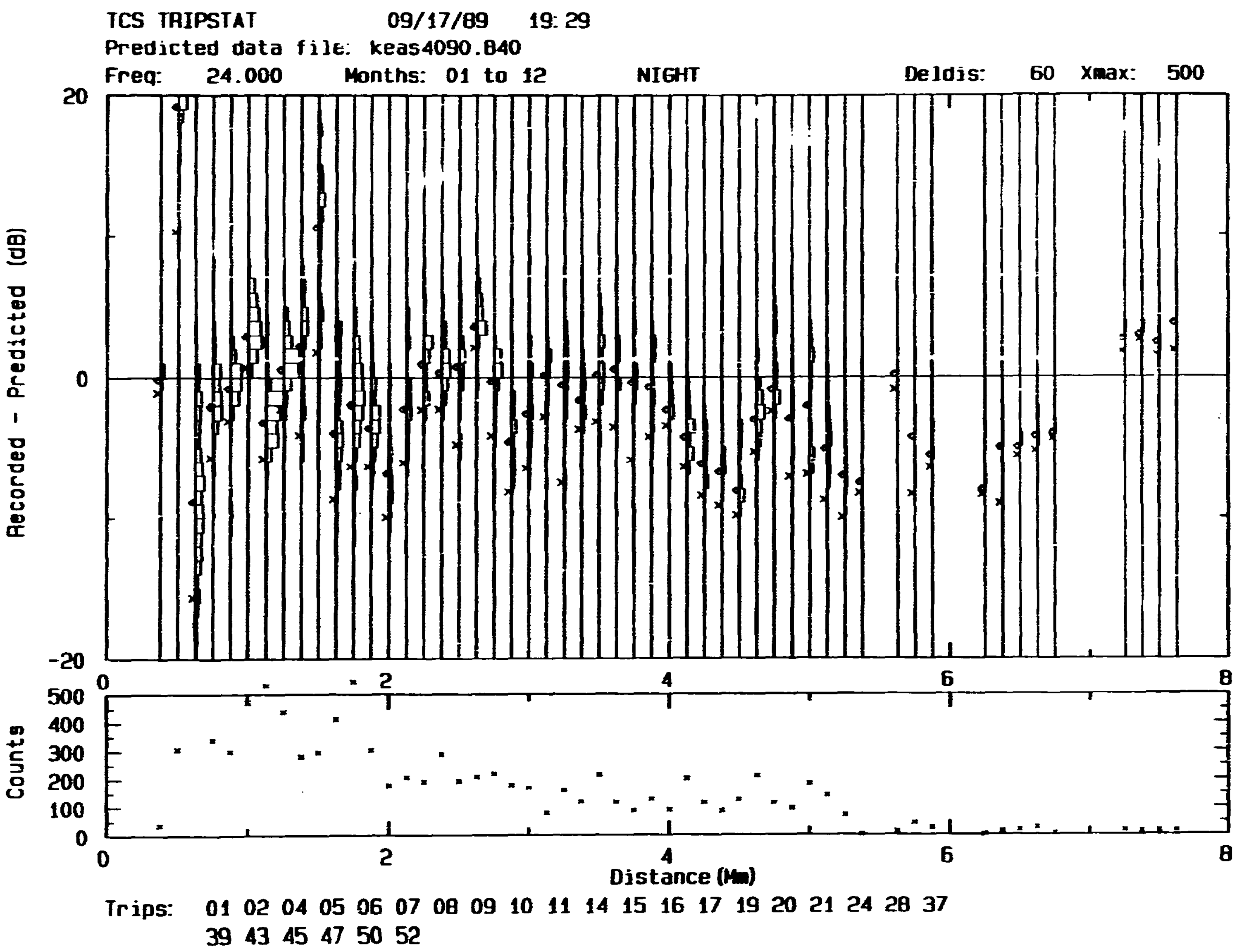


Figure 55. Recorded – predicted data, Cutler at 1000 kW, 24.0 kHz, with LWPC prediction for $\beta = 0.54$, $h' = 84$, PCAP = 70-74.

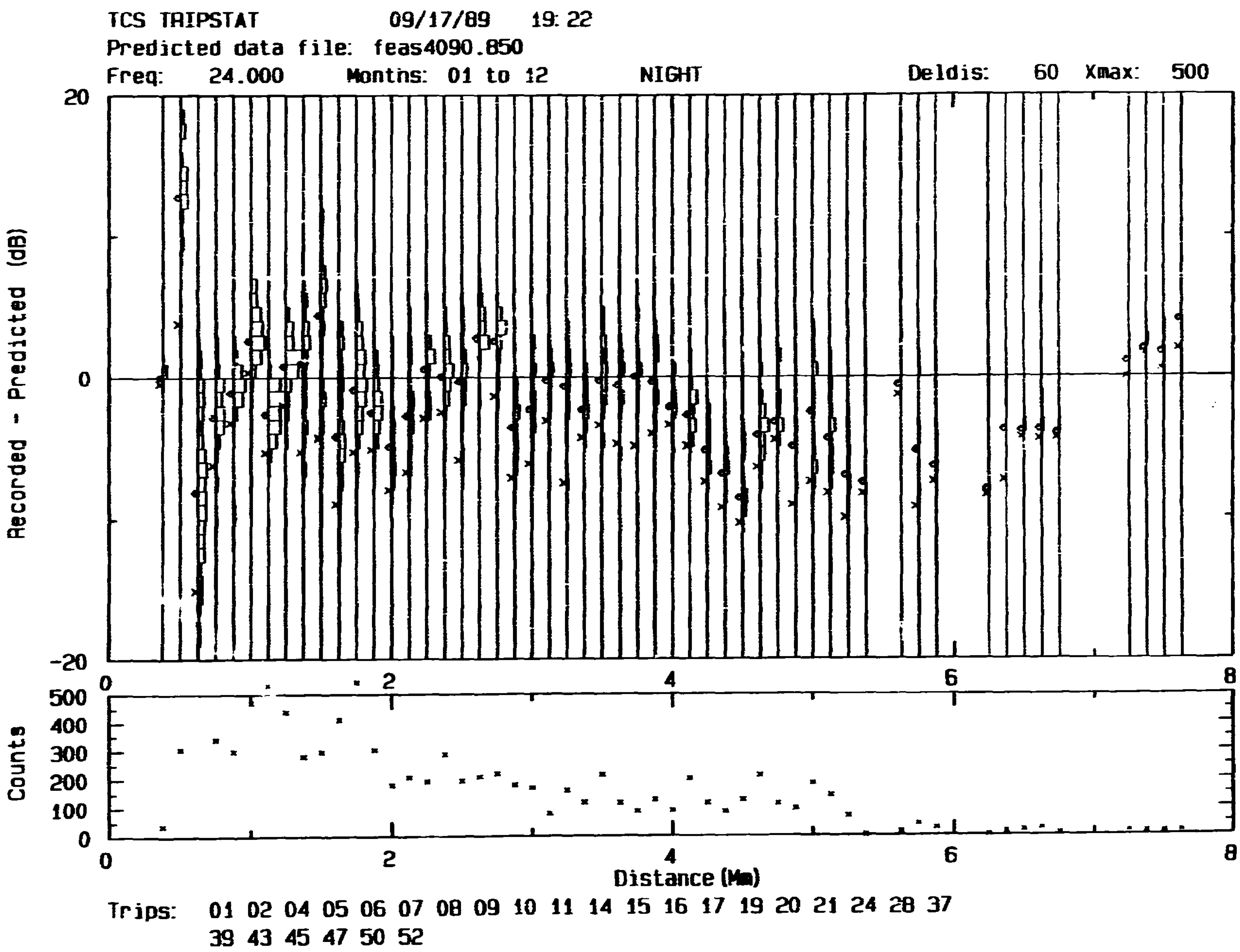


Figure 56. Recorded − predicted data, Cutler at 1000 kW, 24.0 kHz, with LWPC prediction for $\beta=0.54$, $h'=85$, PCAP=70-74.

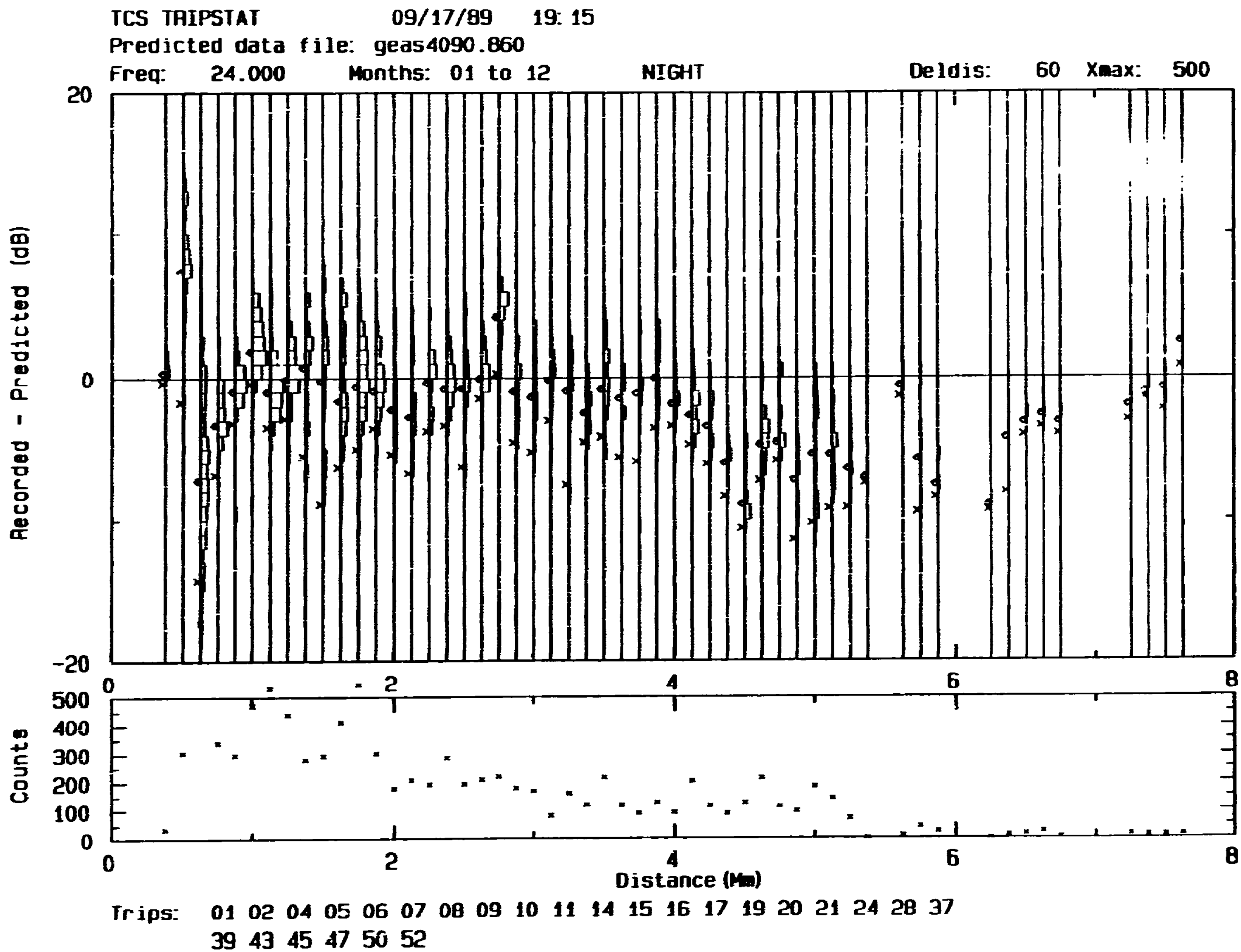


Figure 57. Recorded − predicted data, Cutler at 1000 kW, 24.0 kHz, with LWPC prediction for $\beta=0.54$, $h'=86$, PCAP=70-74.

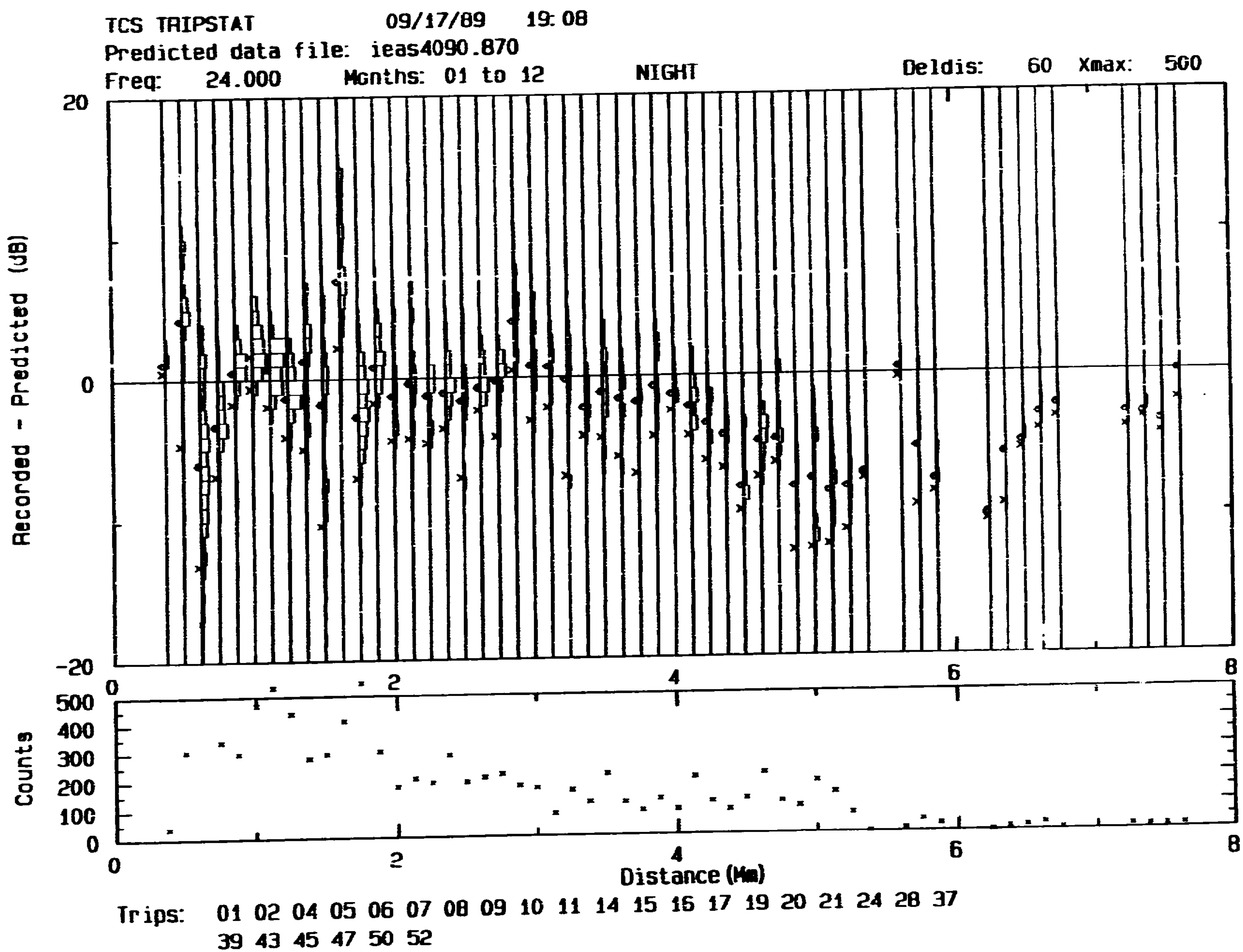


Figure 58. Recorded − predicted data, Cutler at 1000 kW, 24.0 kHz, with LWPC prediction for β=0.54, h′=87, PCAP=70-74.

II-7.5 EXCURSIONS, ANNAPOLIS, 21.4 kHz, WITH PCAP = 80-84

Figures 59-63 examine the statistical characteristics of the 21.4-kHz path with the PCAP adjustment of LWPC disabled. As was seen in the signal vs. distance plots, removal of the PCAP compensation forces the best-fit case to a lower reflection height. The best case for these examples is found at h' = 85 km.

In the 85-km charts of figure 61, most mean values to beyond 5-Mm distance are within ±2 dB of the zero line. This agreement between measured and predicted data is indeed remarkable, given the variable nature of the nighttime ionosphere, and approaches the agreement achieved for the daytime cases of the Callaghan report.

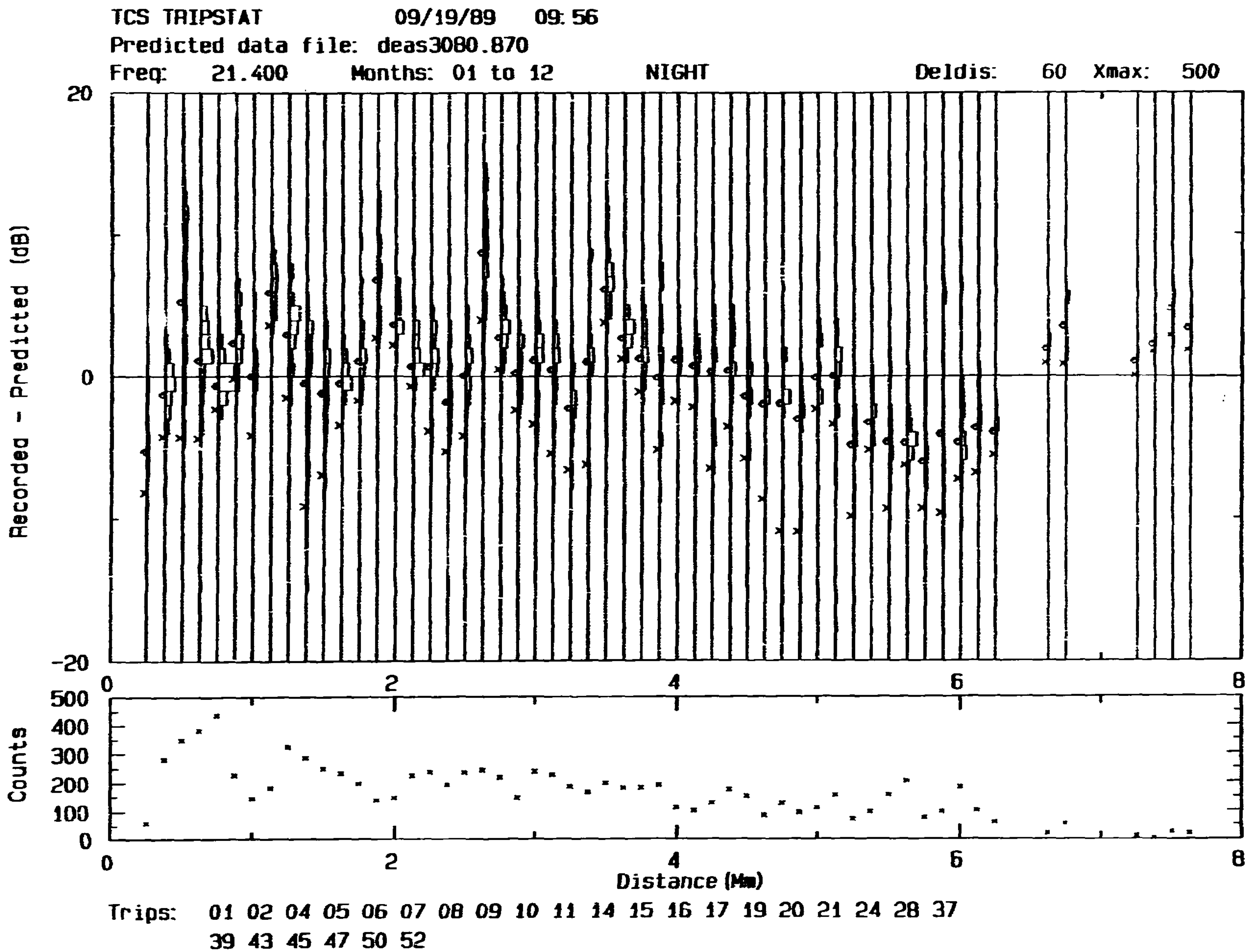


Figure 59. Recorded – predicted data, Annapolis at 250 kW, 21.4 kHz, with default LWPC prediction for $\beta=0.41$, $h'=87$, PCAP=80-84.

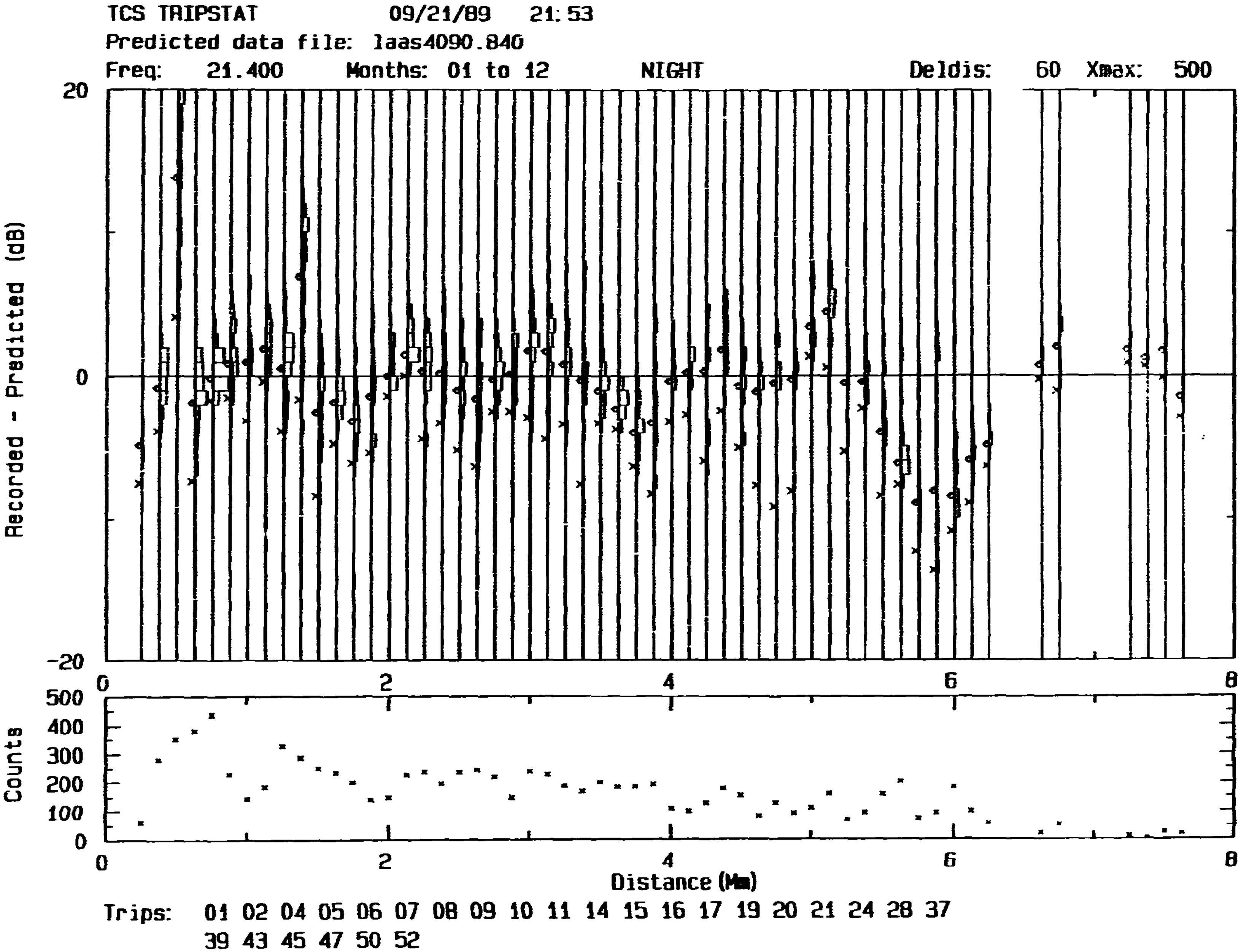


Figure 60. Recorded – predicted data, Annapolis at 250 kW, 21.4 kHz, with LWPC prediction for $\beta=0.51$, $h'=84$, PCAP=80-84.

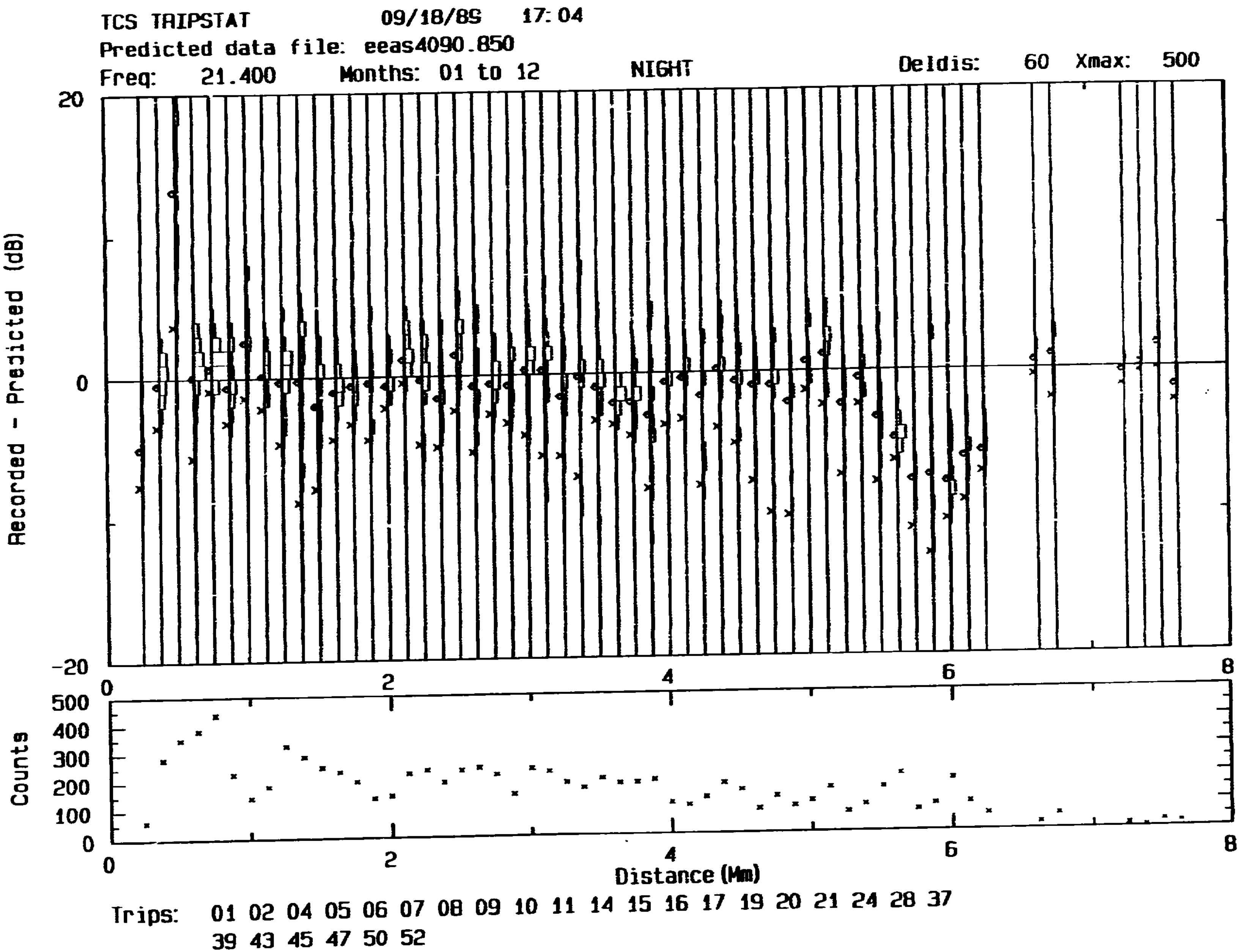


Figure 61. Recorded – predicted data, Annapolis at 250 kW, 21.4 kHz, with LWPC prediction for $\beta=0.51$, $h'=85$, PCAP=80-84.

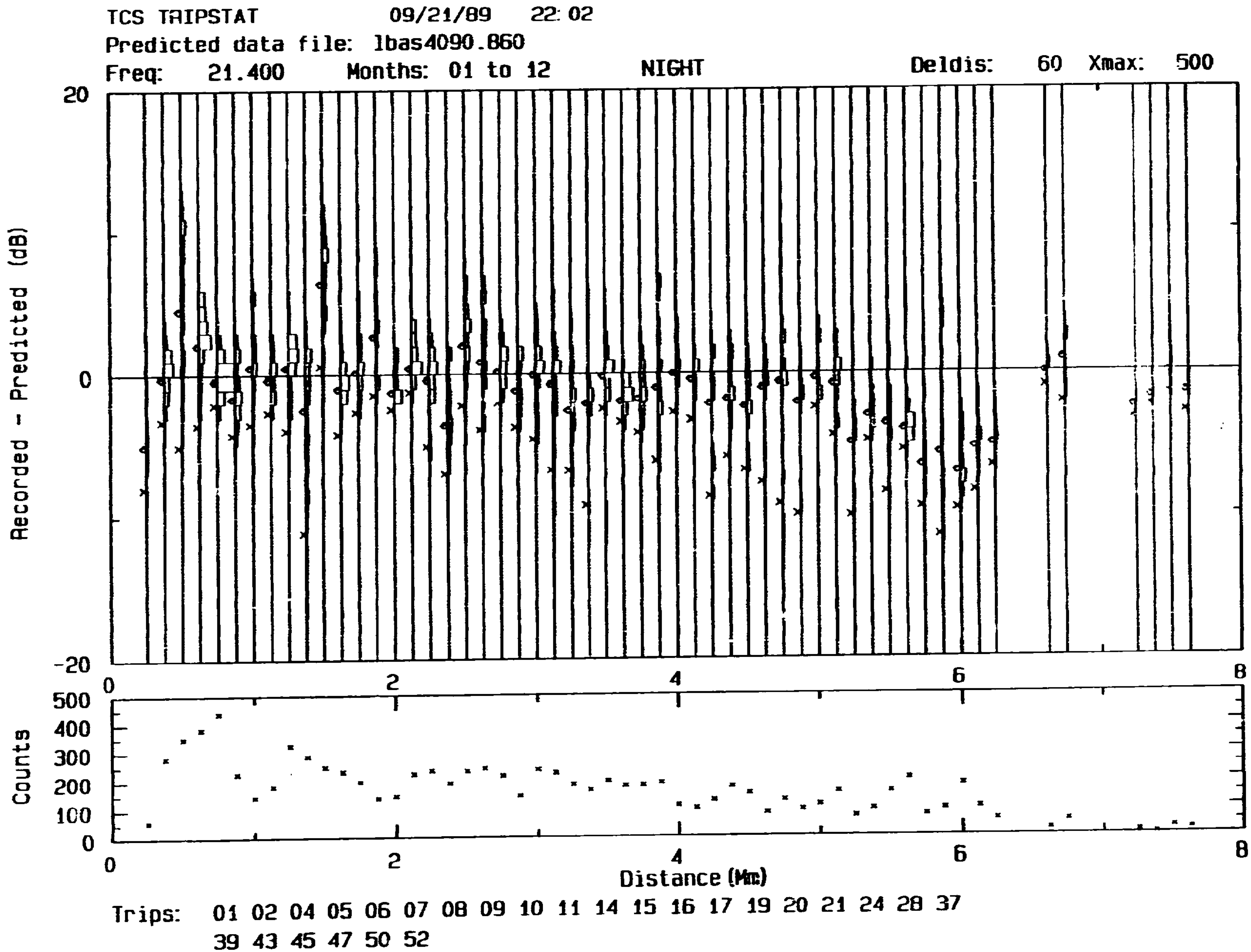


Figure 62. Recorded – predicted data, Annapolis at 250 kW, 21.4 kHz, with LWPC prediction for $\beta=0.51$, $h'=86$, PCAP=80-84.

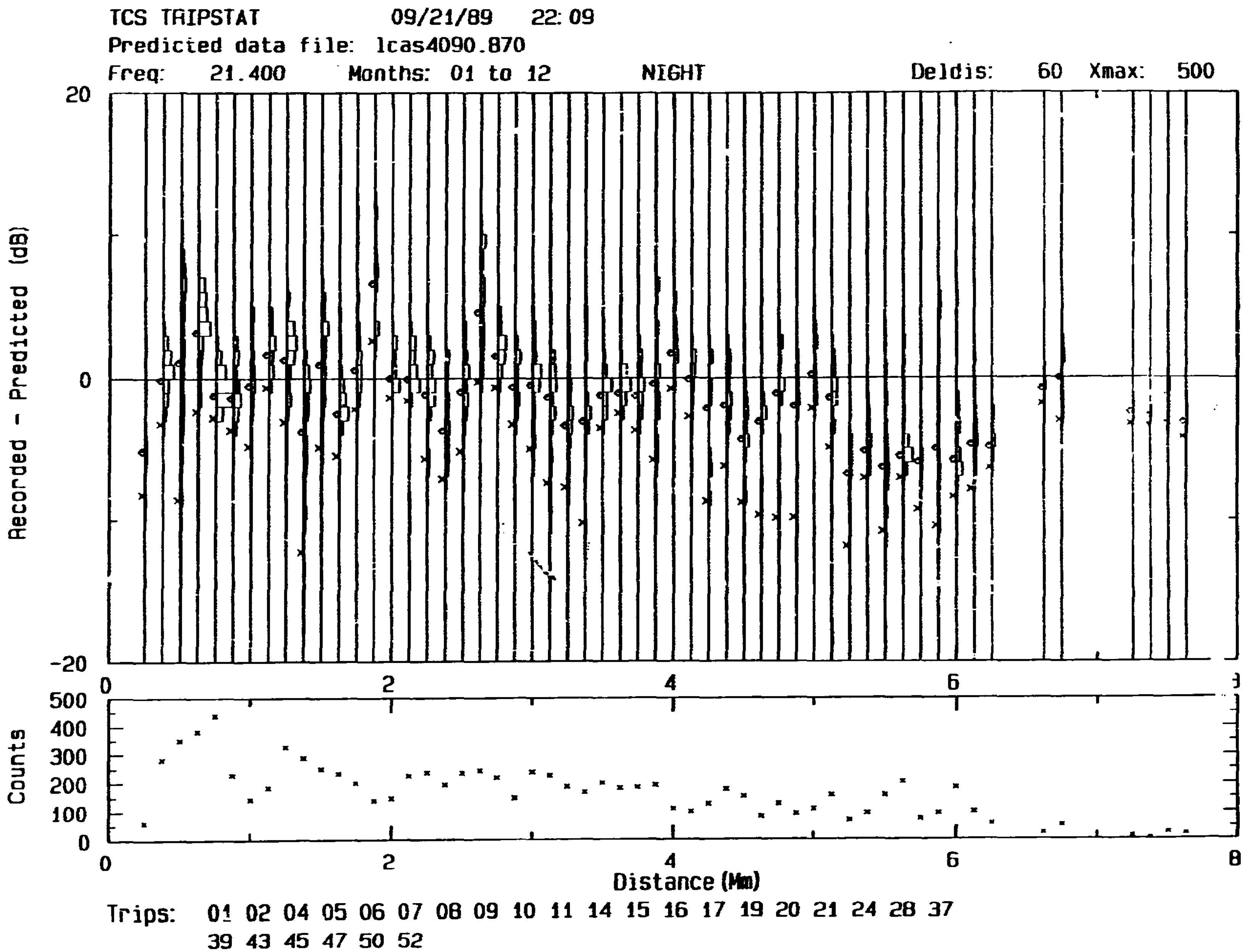


Figure 63. Recorded – predicted data, Annapolis at 250 kW, 21.4 kHz, with LWPC prediction for β=0.51, h′=87, PCAP=80-84.

II-7.6 EXCURSIONS, CUTLER, 24.0 kHz, WITH PCAP = 80-84

The excursions of figures 64-68, for 24.0 kHz, reflect the variability of the signal vs. distance plots seen earlier. Although the fit isn't as good as in the 21.4-kHz examples, the best case is still found at 84 to 85 km. This suggests that the 85-km profile be selected as a standard improvement for all nighttime frequencies, since it would then be a common choice. (A preliminary recommendation for nighttime profiles from the comparisons of this task was presented in figure 1 on page 5.) However, such a decision ignores the effect of LWPC's PCAP adjustment, which certainly must remain in place at some setting to compensate for the lower ionospheres at higher latitudes.

These findings underscore the need for additional analyses of the Callaghan data over a wider range of profiles, and for the investigation of more wide-ranging PCAP selections. The manner in which the statistical comparisons could be automated is discussed in next section.

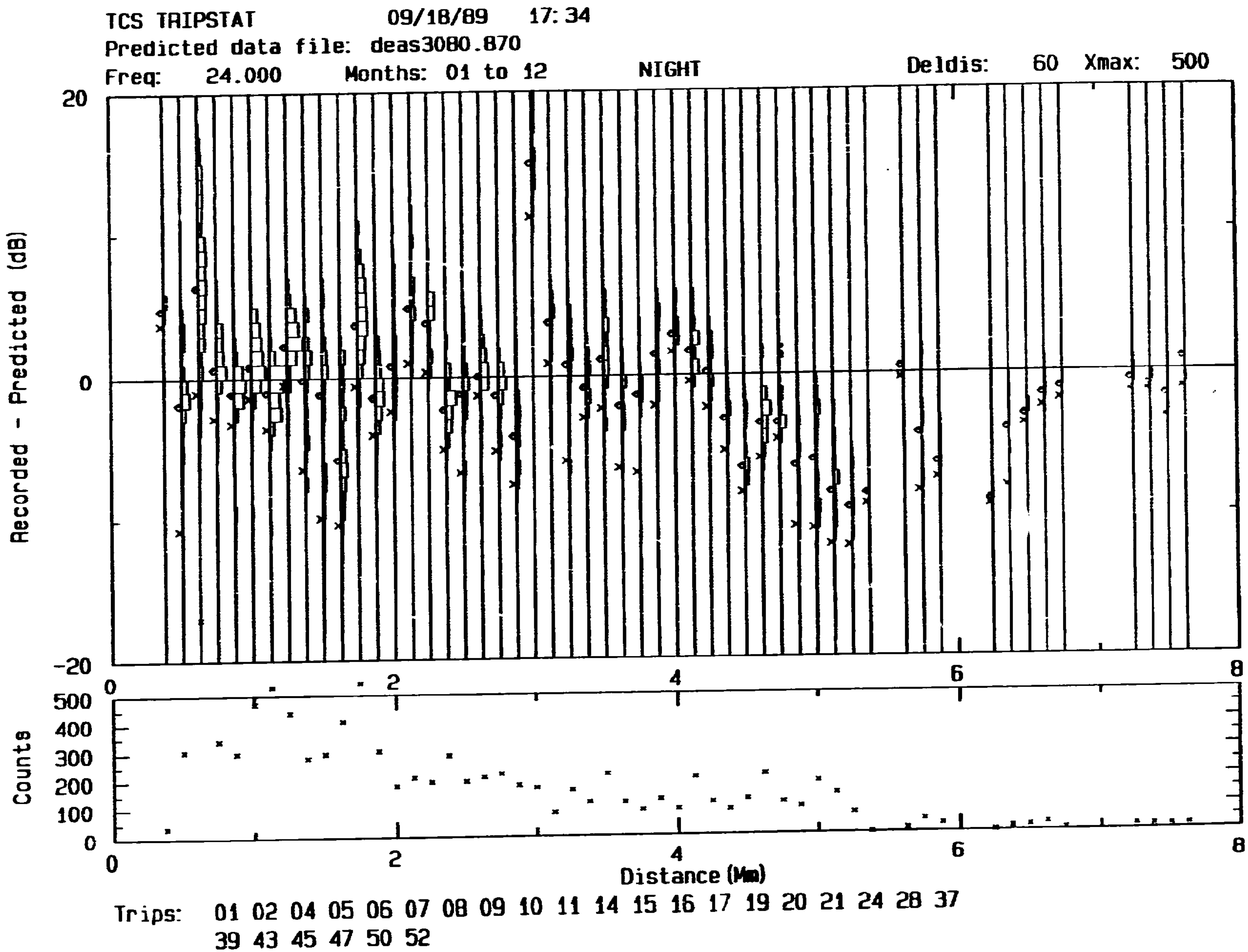


Figure 64. Recorded − predicted data, Cutler at 1000 kW, 24.0 kHz,
h default LWPC prediction for β=0.44, h′=87, PCAP=80-84.

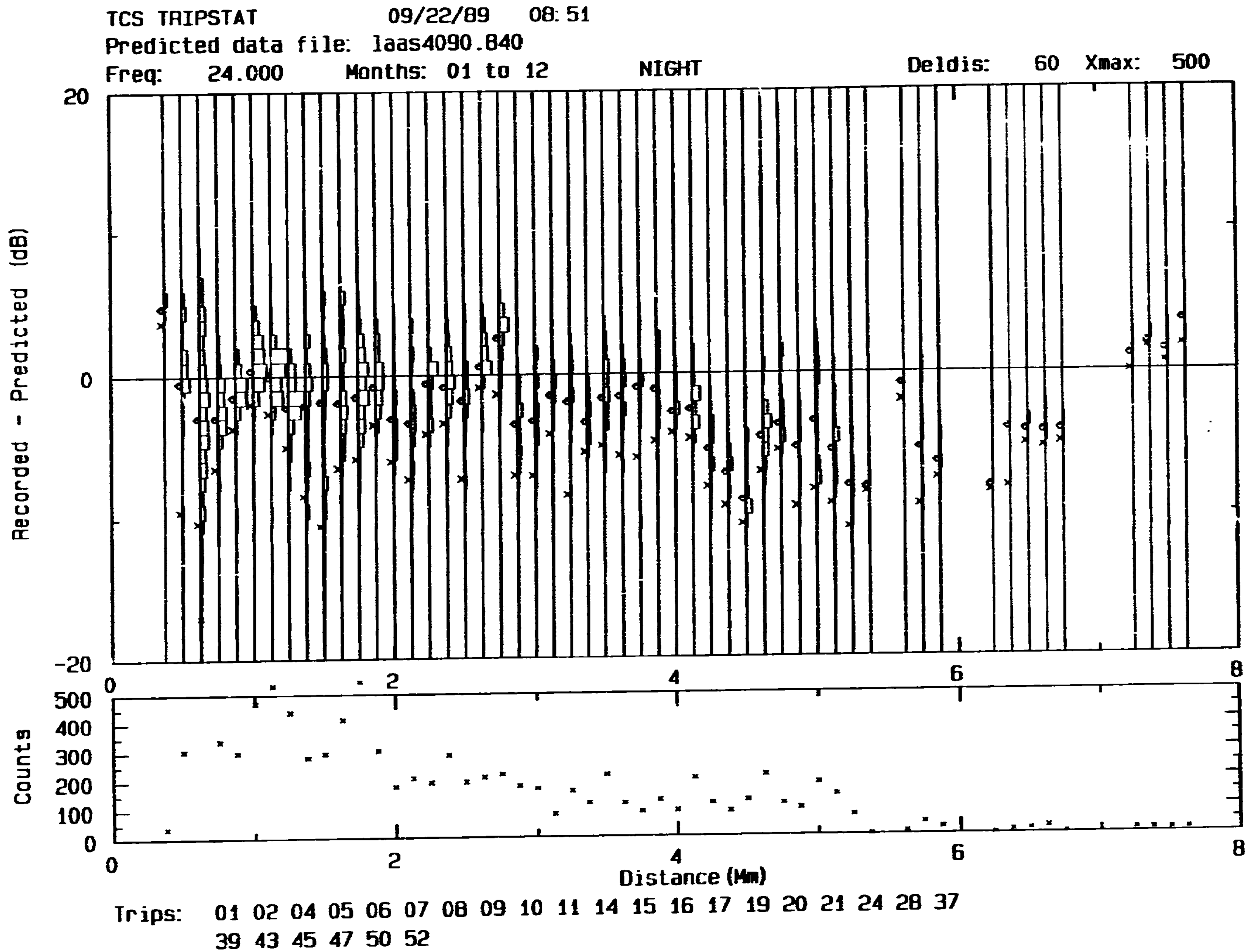


Figure 65. Recorded – predicted data, Cutler at 1000 kW, 24.0 kHz, with LWPC prediction for $\beta=0.54$, $h'=84$, PCAP=80-84.

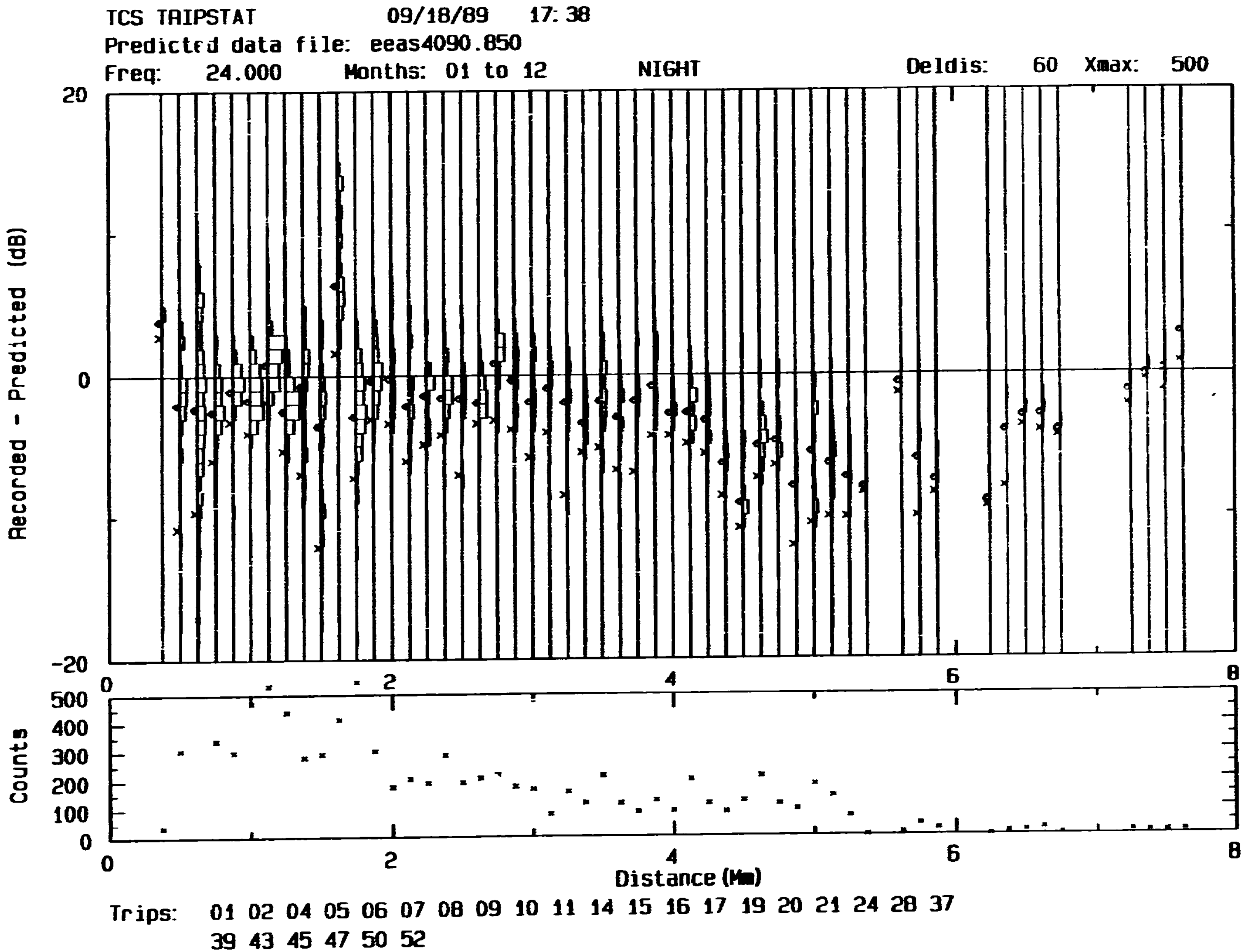


Figure 66. Recorded − predicted data, Cutler at 1000 kW, 24.0 kHz, with LWPC prediction for $\beta=0.54$, $h'=85$, PCAP=80-84.

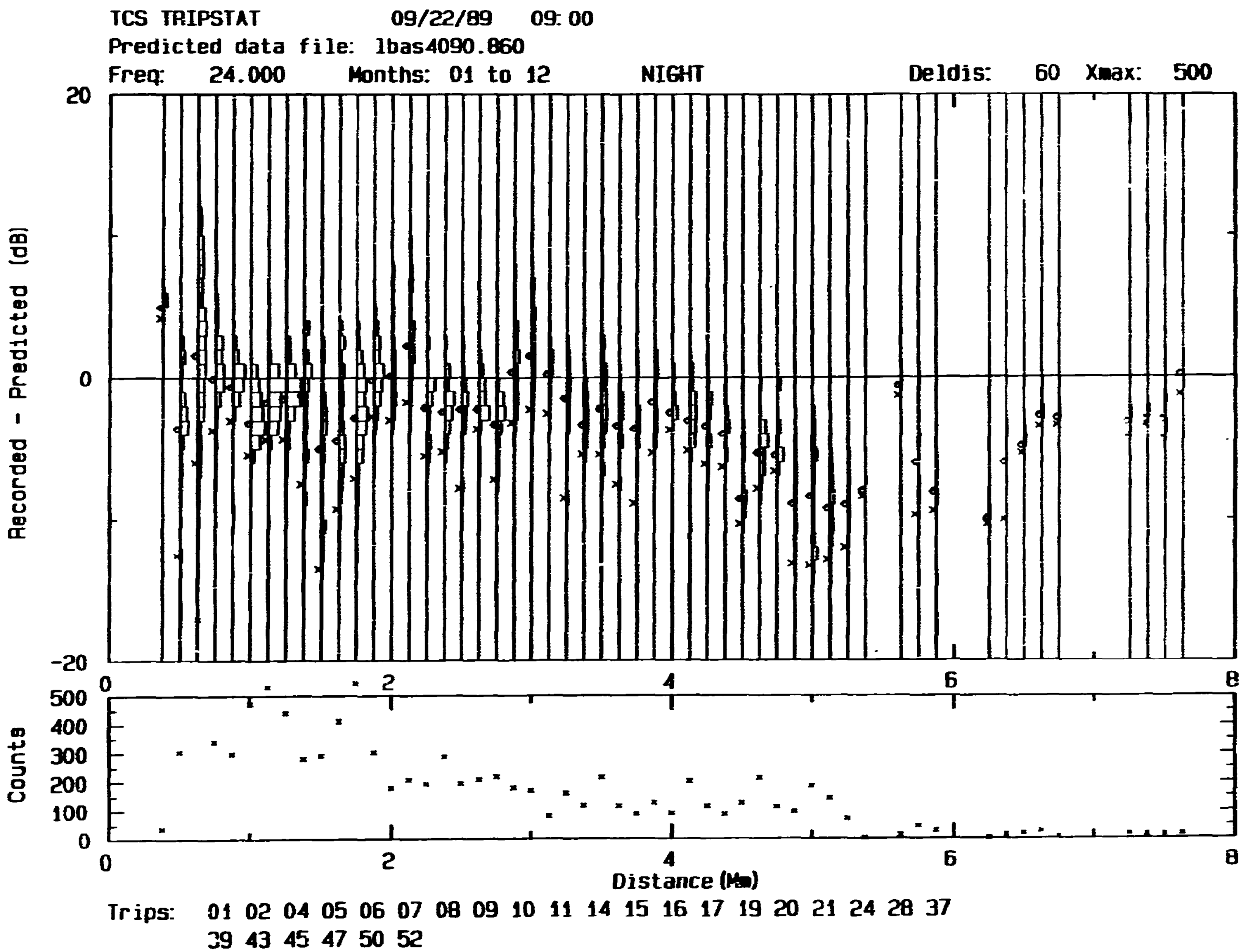


Figure 67. Recorded – predicted data, Cutler at 1000 kW, 24.0 kHz, with LWPC prediction for $\beta=0.54$, $h'=86$, PCAP=80-84.

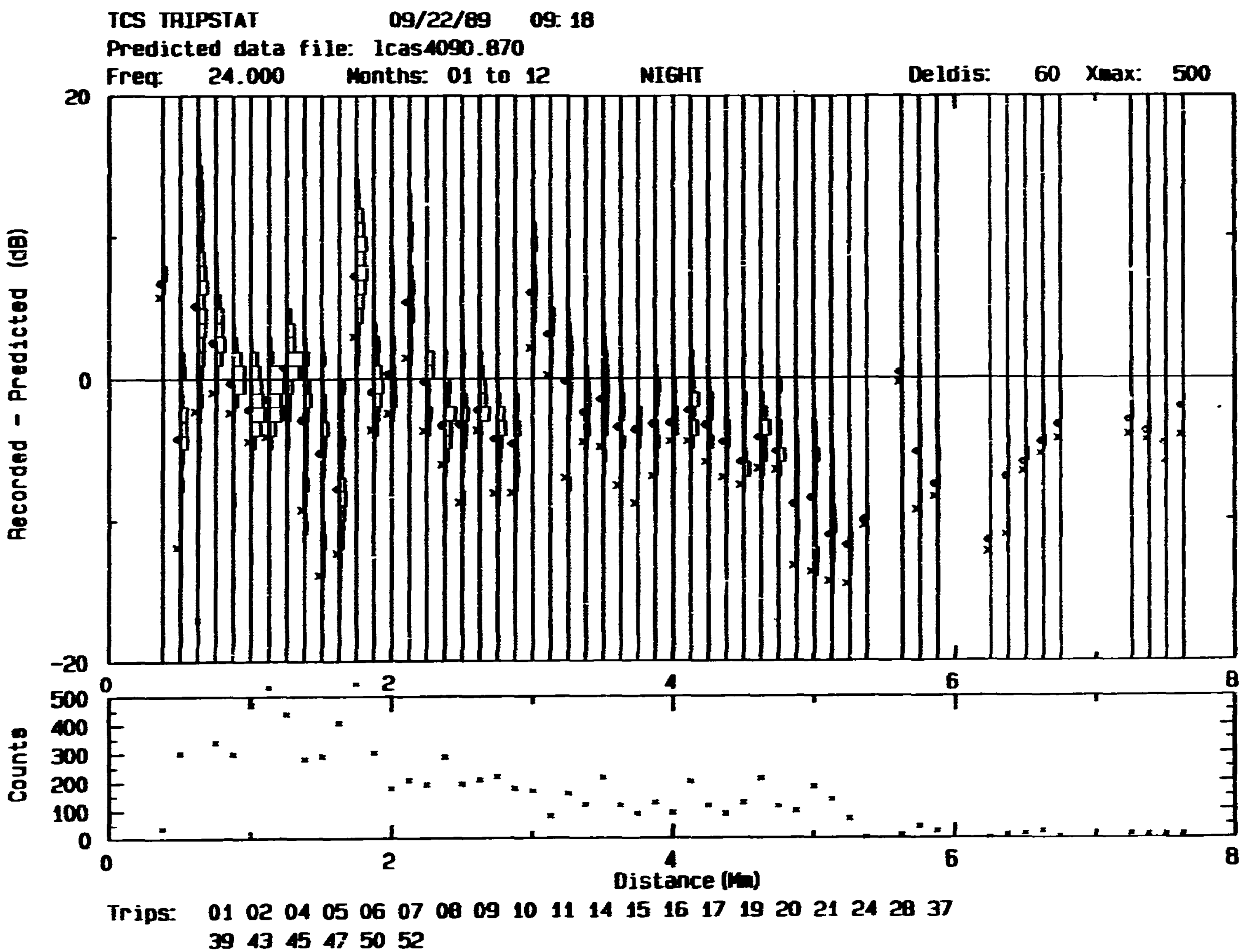


Figure 68. Recorded – predicted data, Cutler at 1000 kW, 24.0 kHz, with LWPC prediction for $\beta=0.54$, $h'=87$, PCAP=80-84.

II-7.7 SUMMARY OF STATISTICAL COMPARISONS

The previous sections showed that TRIPSTAT statistical charts provide a means for quantitative evaluation of recorded-minus-predicted data that is superior to the analyst's subjective judgment. Still, the comparison of one statistical chart against another requires a similar visual appraisal.

As a way of further mechanizing the comparisons, an average of all the histogram mean values was determined for each chart over given distance ranges. Then, a single number was derived for each profile and distance range, and these numbers were graphed over a range of profile choices. Graphs of the average of mean values appear in this section, and represent summaries of the final profiles selected for comparison.

Similarly, standard deviations of each histogram were computed from the mean and 90% exceedance levels and were averaged for each chart over a particular distance range, assuming a normal distribution of data. Again, a single number corresponding to average standard deviation was derived for each profile and distance, and these numbers were graphed for a range of profile choices.

Figures 69-74 present graphs of averages of the mean and standard deviation values vs. h′ for the selected β range of 0.40-0.90. Figures 69-72 summarize the four analysis frequencies, using the default PCAP settings of 70-74. Summaries of the 21.4- and 24.0-kHz excursions with PCAP = 80-84 are given in figures 73-74. In each graph, averages for five distance ranges are given, and a point representing the single average for the LWPC default profile at a 0-5 Mm range is also shown.

Choosing a profile where the summary graph average of means is at a minimum is the final step of the analysis process. For example, in figure 70 for 19-kHz, the 0-5 Mm curve shows the lowest average mean at an h′ just below 85 km.

A scan of the summary curves confirms that h′ = 85 km is a good choice for the β = 0.40-0.90 profile range, providing that PCAP = 80-84 at the higher frequencies. Ideally, three-dimensional plots with both β and h′ treated parametrically over a much wider profile range should be produced, and PCAP adjustment effects should be investigated.

The summary graphs show how the technique for finding the average of means and standard deviations can aid in the optimization process. The summaries of this task were derived manually from the TRIPSTAT charts. Future tasks should facilitate the process by adding program routines to automatically produce listings and graphs of such averages from a full range of β–h′ profiles.

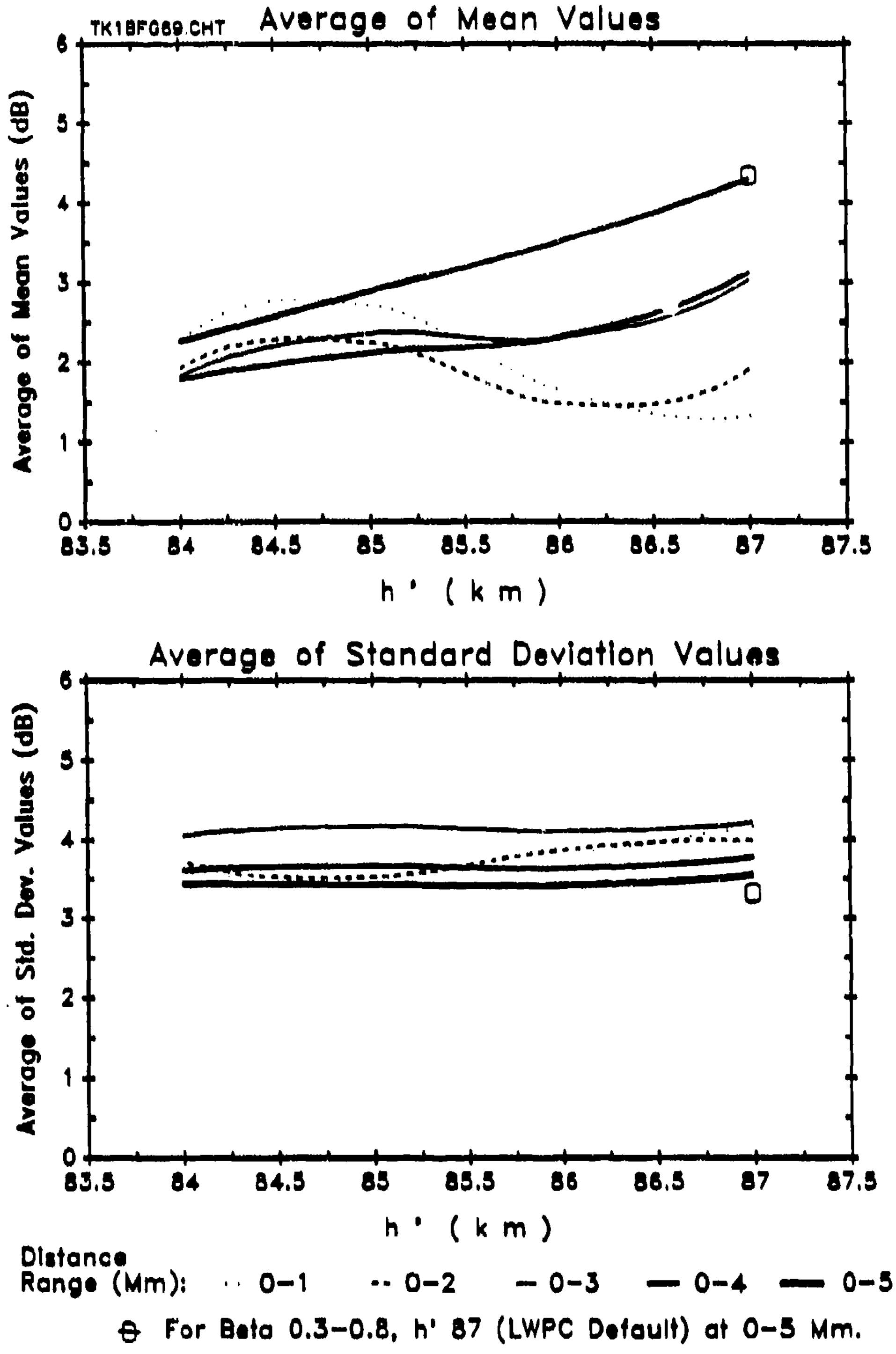


Figure 69. Average of mean and standard deviation values vs. h', recorded – predicted data for Rugby, 65 kW, 16.0 kHz, for β range 0.40-0.90, PCAP = 70-74.

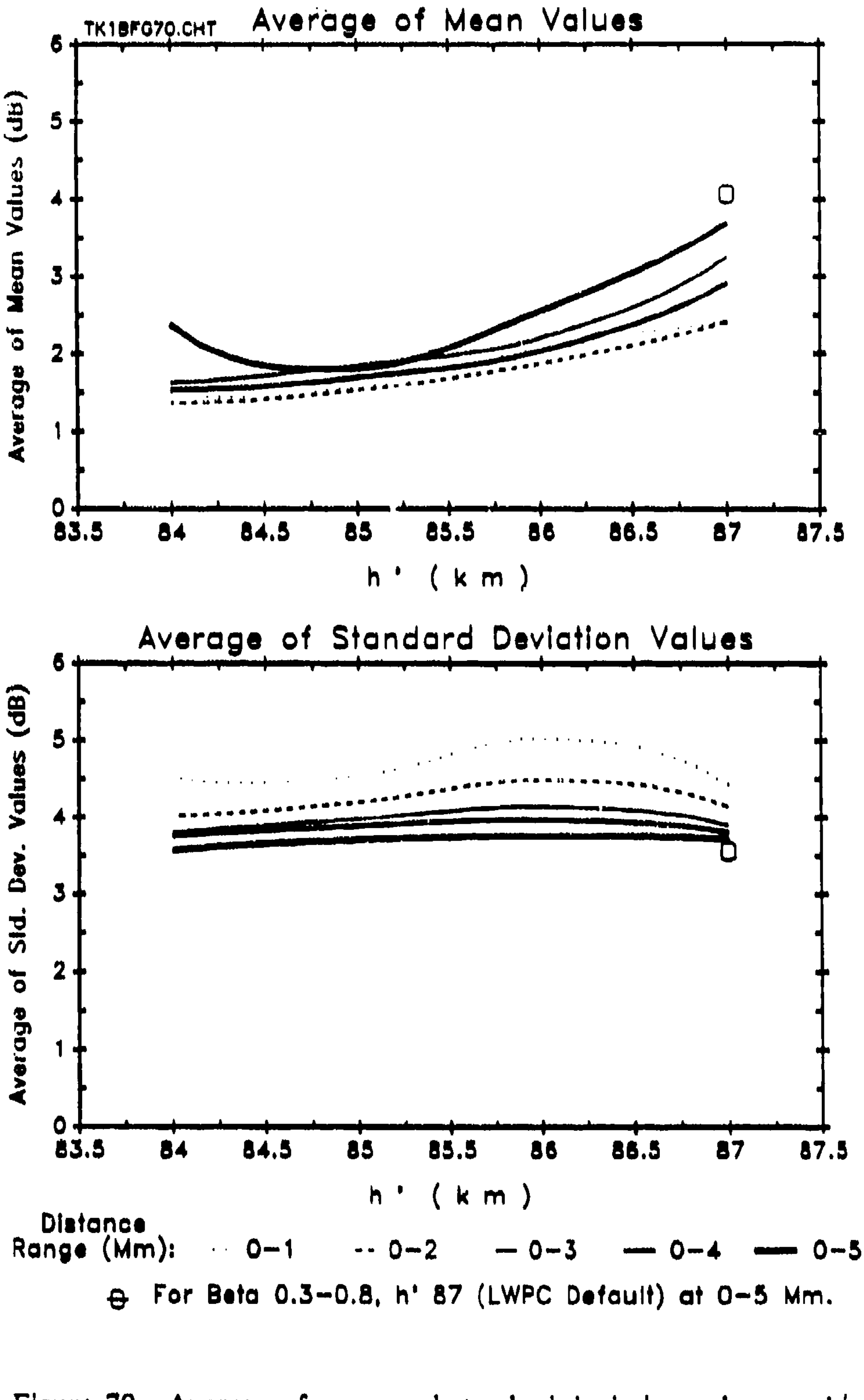


Figure 70. Average of mean and standard deviation values vs. h′, recorded – predicted data for Anthorne, 80 kW, 19.0 kHz, for β range 0.40-0.90, PCAP = 70-74.

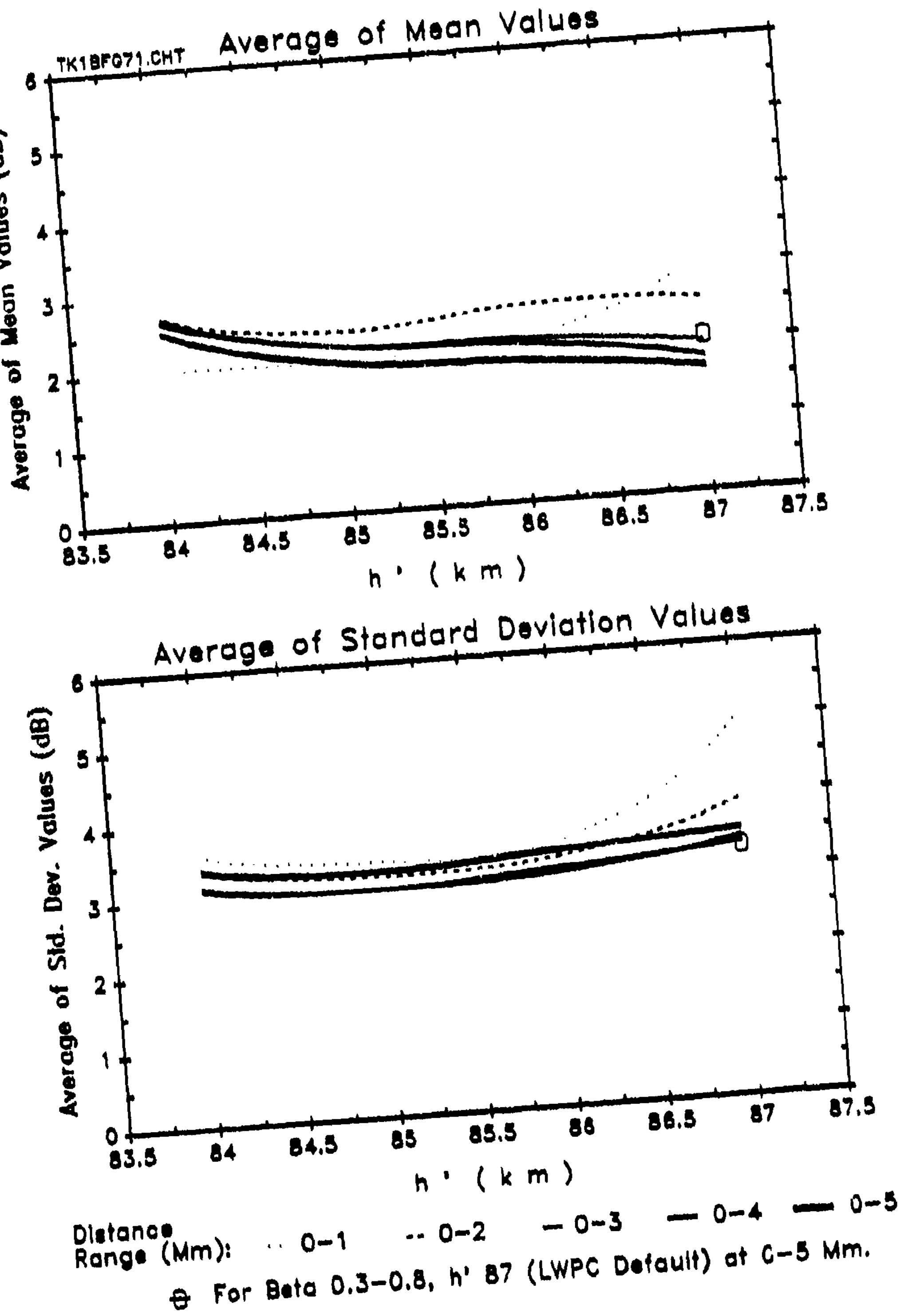


Figure 71. Average of mean and standard deviation values vs. h', recorded – predicted data for Annapolis, 250 kW, 21.4 kHz, for β range 0.40-0.90, PCAP = 70-74.

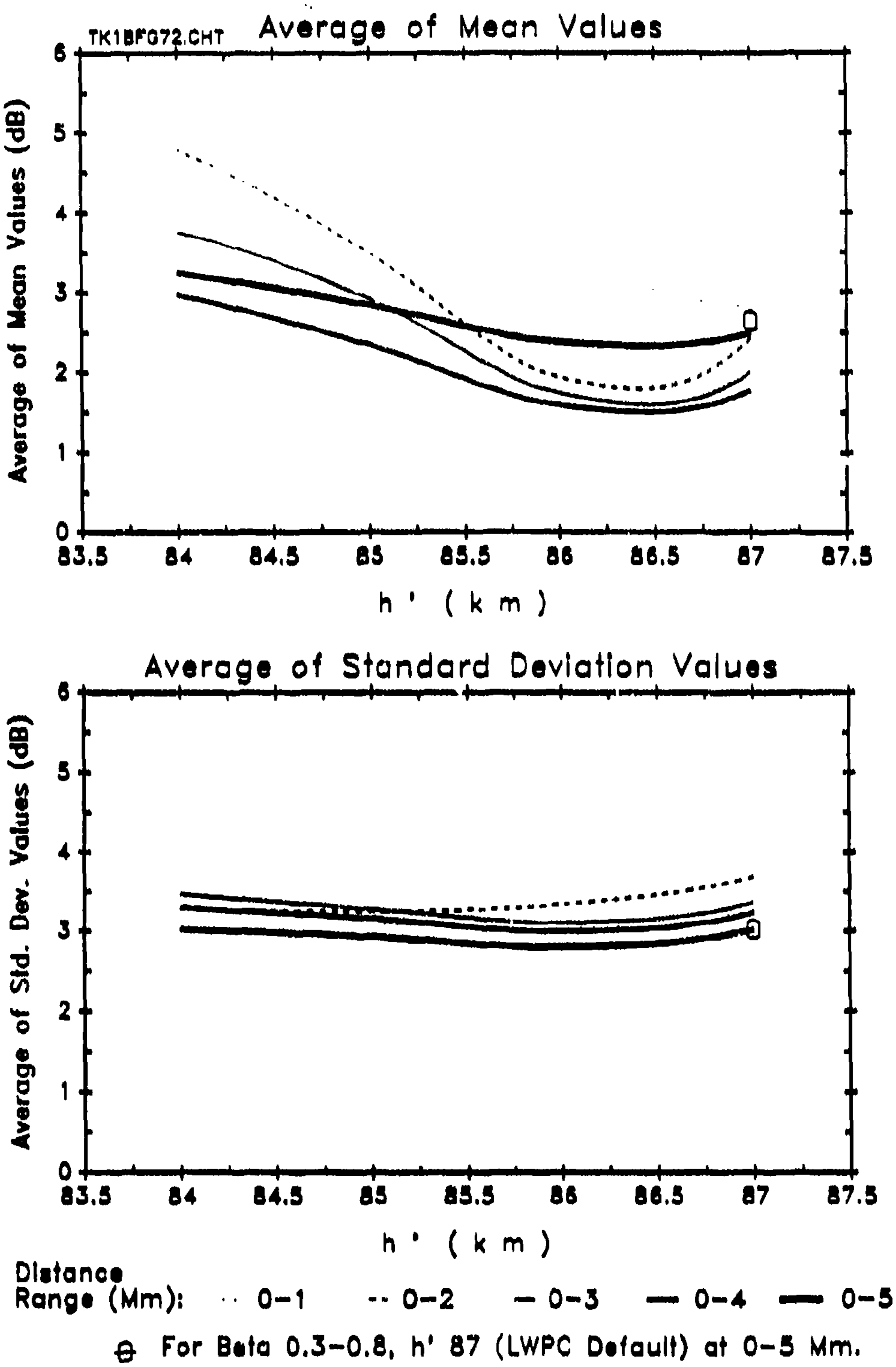


Figure 72. Average of mean and standard deviation values vs. h', recorded – predicted data for Cutler, 1000 kW, 24.0 kHz, for β range 0.40-0.90, PCAP = 70-74.

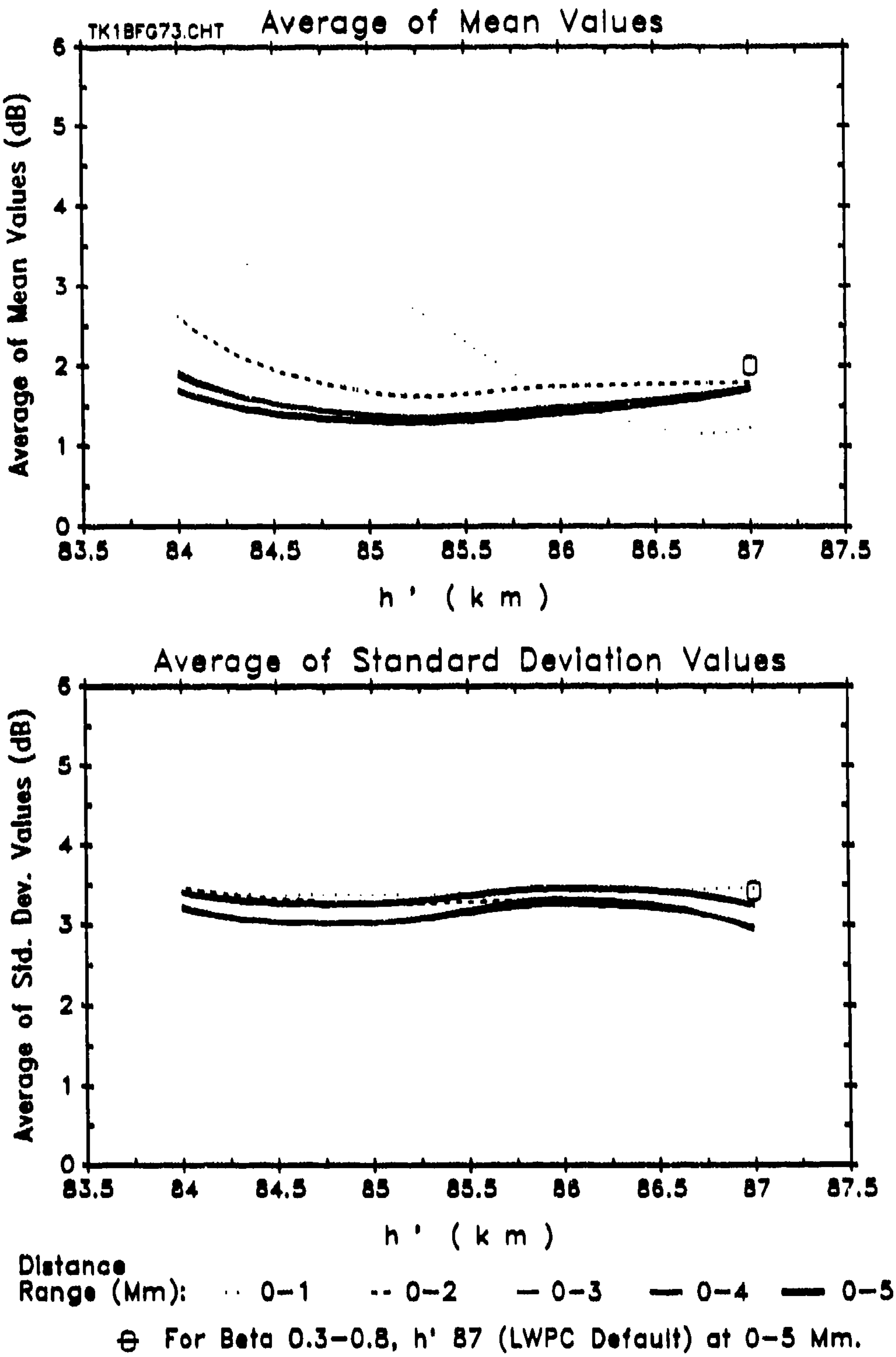


Figure 73. Average of mean and standard deviation values vs. h', recorded – predicted data for Annapolis, 250 kW, 21.4 kHz, for β range 0.40-0.90, PCAP = 80-84.

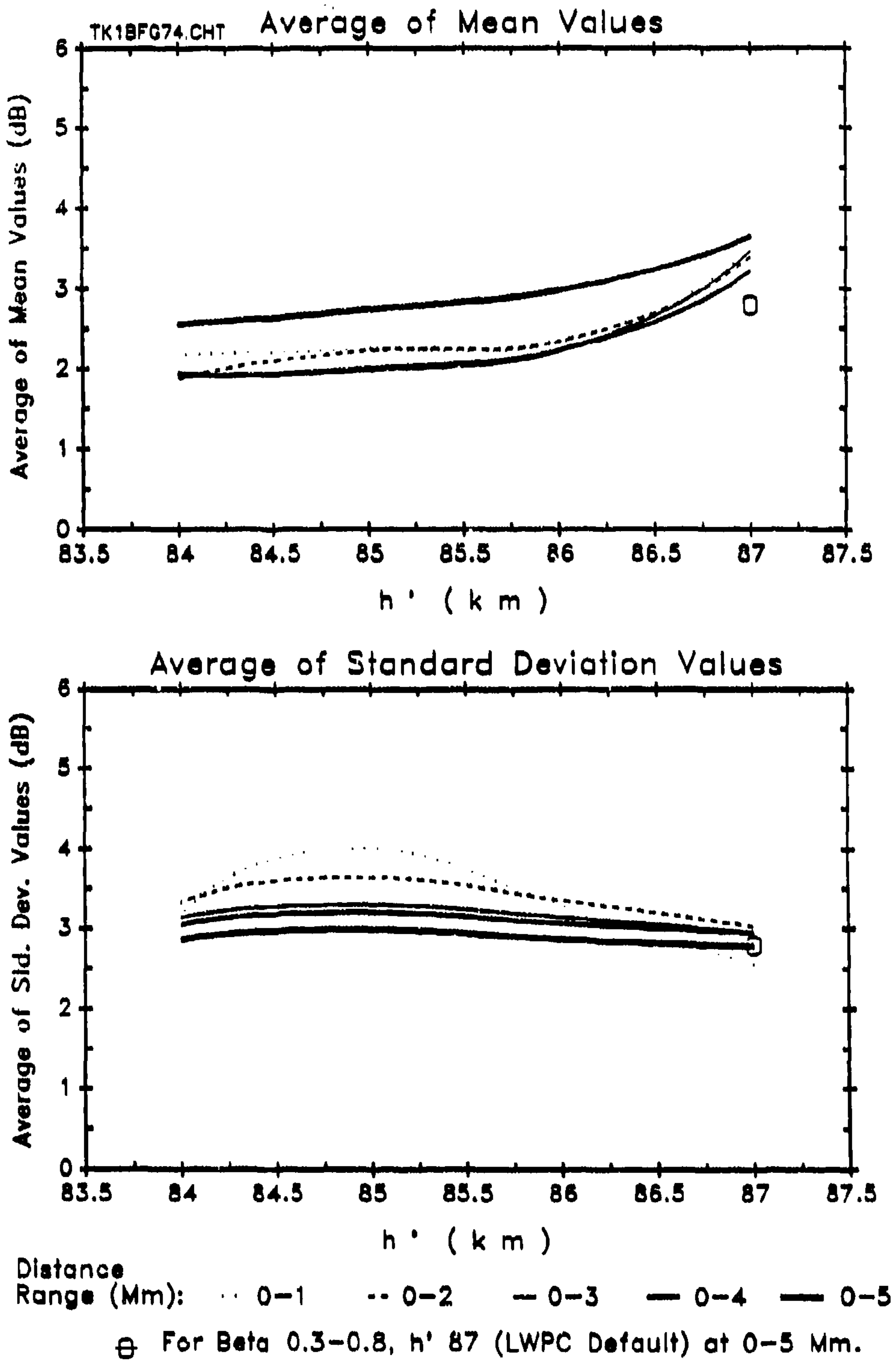


Figure 74. Average of mean and standard deviation values vs. h', recorded – predicted data for Cutler, 1000 kW, 24.0 kHz, for β range 0.40-0.90, PCAP = 80-84.

SECTION 8

CONCLUSIONS

All objectives of Part 1 of the present task have been met, and the following conclusions have been made.

- The analysis methodology of the Callaghan report has been reproduced, and comparable output graphics and data reduction techniques have been reduced to practice. The NOSC LongWave Prediction Capability (LWPC) family of programs has been installed on task computers in an emulated VAX-VMS environment and usage has been validated against NOSC-supplied test cases.
- The daytime analyses of the Callaghan report have been repeated with nearly identical results, as a further measure of methodology validation. Example predictions of the same type have been produced for the nighttime environment, and initial comparisons with recorded data at 21.4 kHz show good agreement.
- Statistical summary graphs should be expanded to also include distance ranges of 1-5, 2-5, 3-5 and 4-5 Mm.
- It is evident that separate graphs of recorded data by trip will be helpful in eliminating questionable data and in optimizing a preferred set of aggregate data for each frequency. Such optimized sets of recorded data should be routinely assembled before profile modifications are attempted.
- Because the presence of significant high-order mode interaction tends to modify the dominant mode propagation signature, and because this effect varies with frequency, the optimization of nighttime profiles is expected to be complex. Profile modifications for the nighttime VLF environment – the main objective of this task – should therefore be recommended only after all available frequencies are considered.
- The Callaghan report examined four VLF frequencies: 16.0, 19.0, 21.4 and 24.0 kHz. Data from the other VLF channels of the recorded database (16.4, 24.8 and 28.5 kHz) should also be examined within the constraints of time and funding.
- If possible, future analyses should separate recorded data into areas of latitude below and above the codip $= 20^\circ$ point where the present LWPC design forces a profile change.

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This document presents final results from a VLF/LF data analysis task initiated in support of the VLF/LF propagation modeling program being developed by NOSC. Specifically, this document gives the results of comparisons between VLF signal measurements recorded during nighttime hours and NOSC model predictions for similar nighttime propagation paths.

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